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CTI-CRYOGENICS

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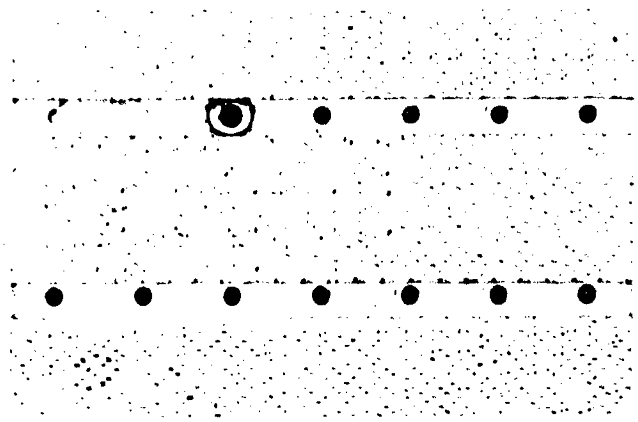

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HIGH PERFORMANCE SPLIT-STIRLING COOLER PROGRAM

FINAL TECHNICAL REPORT

September 1982

Prepared for

NIGHT VISION AND ELECTRO-OPTICS LABORATORIES

Contract DAAK70-79-C-0152

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. A123768
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) HIGH PERFORMANCE SPLIT-STIRLING COOLER PROGRAM	5. TYPE OF REPORT & PERIOD COVERED Final Technical Sept. 1979 - Sept. 1982
	6. PERFORMING ORG. REPORT NUMBER M8040111
7. AUTHOR(s) Richard P. Meeker	8. CONTRACT OR GRANT NUMBER(s) DAAK70-79-C-0152
9. PERFORMING ORGANIZATION NAME AND ADDRESS CTI-CRYOGENICS, A Division of Helix Technology Corporation, 266 Second Avenue, Waltham, Massachusetts 02254	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Electronics Research and Dev. Command Night Vision and Electro-Optics Laboratories Fort Belvoir, Virginia 22060	12. REPORT DATE September 1982
	13. NUMBER OF PAGES 102
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Cryogenic Refrigerator, Split-Stirling System, Cryogenic Cooler, 1 Watt Cooling System, Remote Expander, Compressor/Motor Assembly

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the physical characteristics of the final design configuration of the 1 Watt Split-Stirling Cryogenic Cooler designed, developed, and qualification tested by CTI-CRYOGENICS under contract No. DAAK70-79-C-0152 for the Army Night Vision and Electro-Optics Laboratories. Qualification testing included evaluation of the 1.0 Watt Cryogenic Cooler under the following conditions:

20. Abstract (continued)

- Performance tests over the temperature range of -40°C to +55°C,
- High and Low Temperature Shock Tests,
- Mechanical Shock Tests,
- Sinusoidal Vibration
- Self-Induced Vibration
- Acoustical Testing
- 1000 Hour Mean Time Between Failure Life Tests.

The cryogenic cooler design consists of a motor and compressor assembly, and a remote expander assembly, interconnected by a stainless steel capilliary line. The system is nominally a 18.5 VDC, 60 Watt cooler and has a maximum weight of 4 pounds.

This report summarizes the results of the performance, environmental and life qualification tests conducted under the contract and provides supporting data for each of the test catagories.

FINAL TECHNICAL REPORT

FOR PERIOD FROM

SEPTEMBER 1979 TO SEPTEMBER 1982

HIGH PERFORMANCE SPLIT STIRLING COOLER PROGRAM

SEPTEMBER 1982

Prepared for

U.S. Army Electronics Research and Development Command
Night Vision and Electro-Optics Laboratories
Fort Belvoir, Virginia 22060

Prepared by

CTI-CRYOGENICS
A Division of Helix Technology Corporation
266 Second Avenue
Waltham, Massachusetts 02254

PREFACE

CTI-CRYOGENICS, A Division of Helix Technology Corporation, submits this report to the U.S. Army Night Vision and Electro-Optics Laboratories, (NV & EOL), Fort Belvoir, Virginia as required by Contract DAAK70-79-C-0152, sequence number A002, entitled Final Technical Report.

This report documents the end results of the technical activity associated with the design, fabrication and testing of six High Performance Split-Stirling Cryogenic Coolers.

The following personnel contributed to this program:

Richard P. Meeker	CTI-CRYOGENICS	Senior Product Engineer
Noel J. Holland	CTI-CRYOGENICS	Program Manager
Gerald J. Fortier	CTI-CRYOGENICS	Engineering Vice President
Gerald R. Pruitt	CTI-CRYOGENICS	Development Engineering Manager
John E. Kercheval	CTI-CRYOGENICS	Development Engineering Manager
Dr. Bruce R. Andeen	CTI-CRYOGENICS	Development Engineer
Harry G. Nicoll	CTI-CRYOGENICS	Manufacturing Engineer
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Howard Dunmire	NV & EOL	Product Manager

This report was prepared by Richard P. Meeker.

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1.0 INTRODUCTION

On August 21, 1979, CTI-CRYOGENICS entered into a contract with U.S. Army Night Vision and Electro-Optics Laboratories, hereafter referred to as NV & EOL, under Contract DAAK-70-79-C-0152 to design, fabricate and test six (6) cryogenic coolers.

1.1 Design Objectives

1.1.1 The contract objective was to design and fabricate High Performance Split-Stirling Cryogenic Coolers for use on gimballed platforms where low vibration is required and on ground support systems where acoustic noise reduction is required.

1.1.2 The design configuration is required to interface with a Dewar of the gimballed infrared detector-Dewar package defined as B2-28A50102A, to pass the performance cooling requirements, and to be qualified by successfully passing the necessary tests.

1.2 Test Objectives

The test objectives were to pass the following Environmental and Life tests, thereby qualifying the cryogenic cooling systems for military use.

1.2.1 Natural Environmental Tests

- Temperature - shock
- High temperature
- Low temperature
- Performance tests

1.2.2 Dynamic Environmental Tests

- Mechanical shock
- Vibration
- Self-induced vibration
- Acoustics

1.2.3 Life Tests

- 1000 hours MTBF

2.0 PHYSICAL DESCRIPTION

The cryogenic cooler design selected to meet NV & EOL's requirements consists of a compressor assembly, an expander assembly, and a stainless steel capillary interconnecting line as shown in Figure 1. An exploded view of the major components of the cryogenic cooler is shown in Figure 2 with discussion about them as follows:

2.1 Compressor Assembly

The compressor design incorporates a twin-opposed piston configuration housed in a 6061-T6 aluminum crankcase as shown in Figure 3 and is driven by an integral brushless d-c motor. This design approach provides dynamic balancing of the moving parts, thereby minimizing the self-induced vibration. In the selected twin-opposed piston configuration, the working loads on one piston are balanced out by the working loads of the opposite piston. This permits the use of smaller sized ball bearings to carry the load while maintaining desired life characteristics. Only six bearings are used in the compressor; four needle-roller bearings for the two connecting rods and two ball bearings for the motor shaft.

The rotating or crankcase subassembly includes the two drive cranks 180° apart, the two motor bearings, the flywheel and target wheel. This assembly is dynamically balanced to further reduce vibration in the compressor. Heat of compression is removed via finned cylinder heads that are assembled to the compressor crankcase. Gas filling, purging and charging the compressor is accomplished through a purge valve designed by NV & EOL which is incorporated in the compressor housing.

2.2 Compressor Drive Motor

A brushless direct current motor drives the compressor as shown in Figure 2. The motor housing is sealed to the compressor housing by

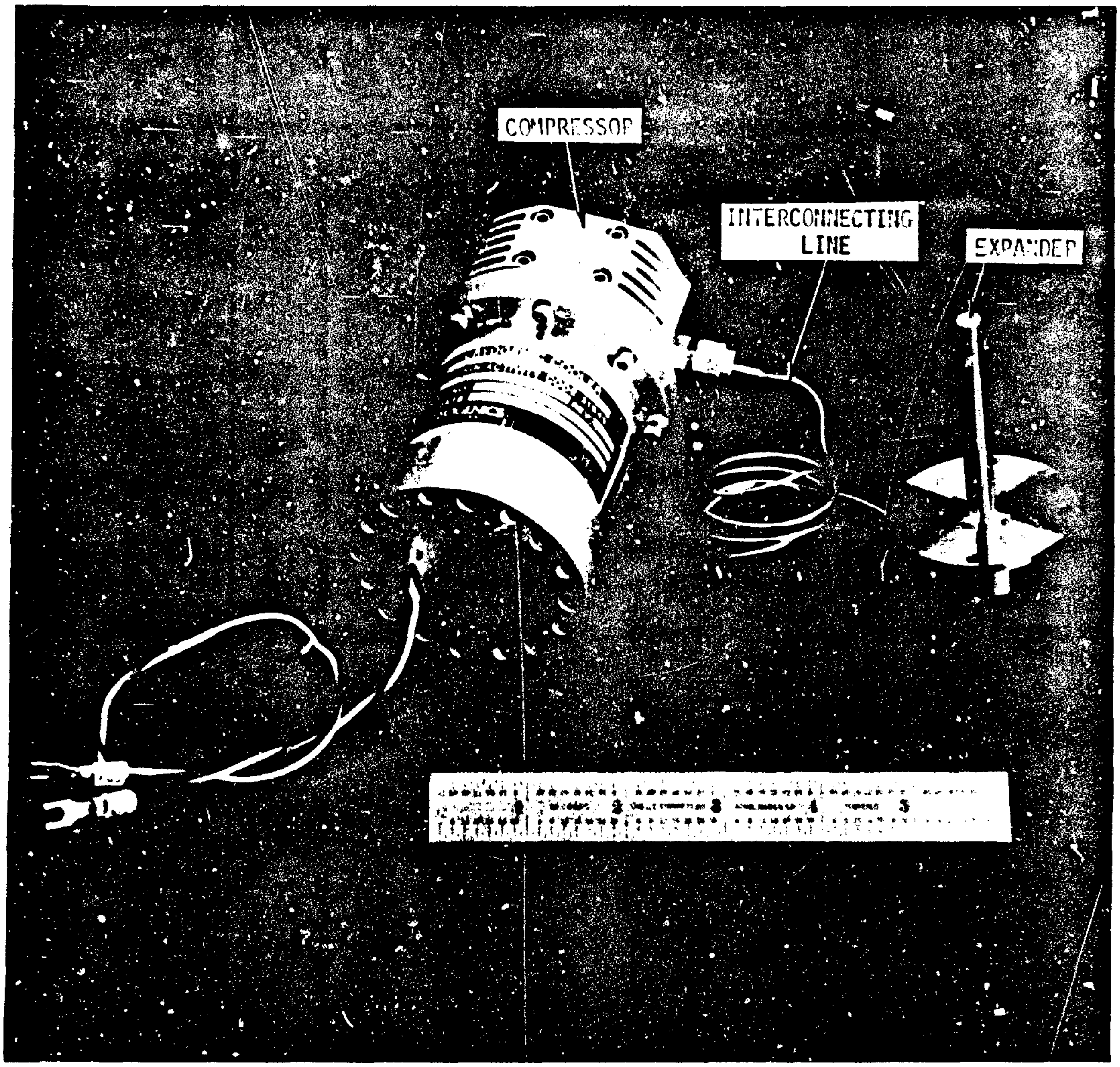


FIGURE 1. 1 WATT/SPLIT-STIRLING CRYOGENIC COOLER ASSEMBLY

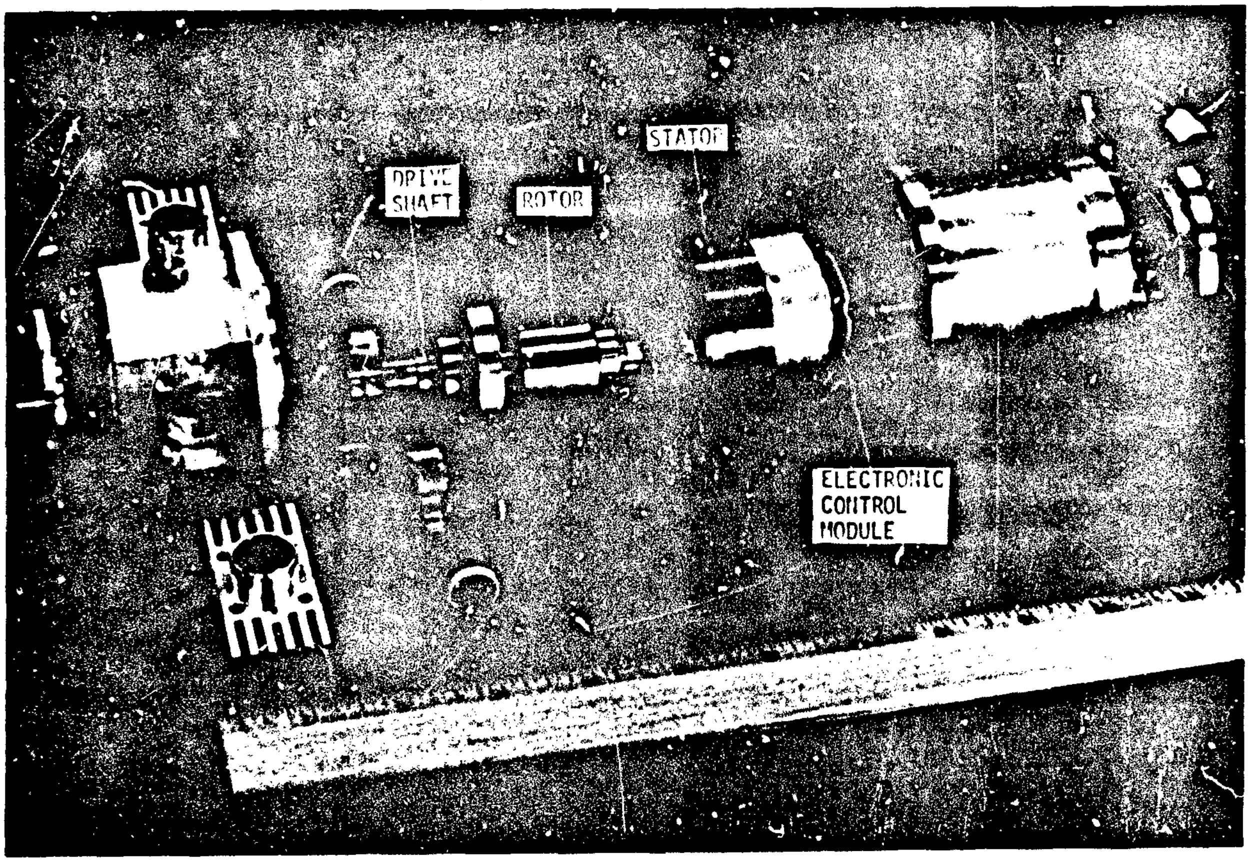


FIGURE 2. CRYOGENIC COOLER-EXPLODED PARTS VIEW

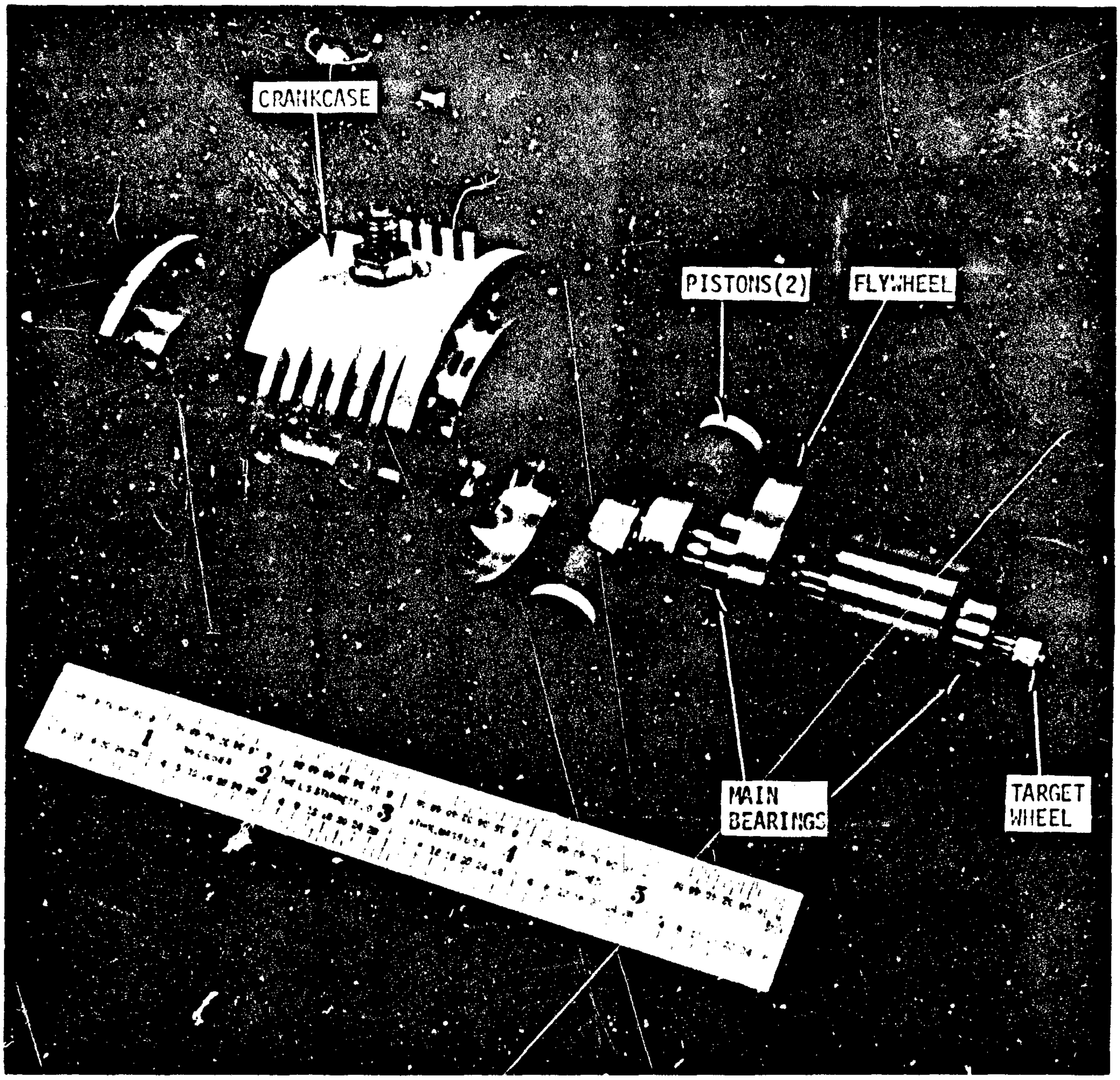


FIGURE 3. COMPRESSOR HOUSING-PISTONS AND CRANKSHAFT

an indium seal and consists of a wound stator, permanent magnet rotor, rotor position targets mounted on the drive shaft, and an electronic control module. The electronic control module contains a hybridized circuit within the motor housing which with a bridge network (Figure 4) provides commutation and switching power to each stator winding. Electrical connections for input power to the motor are made through two hermetically sealed feed-throughs exiting from the rear motor housing cover plate.

2.3 Key Compressor Parameters

- Pressure ratio: 1.7
- Compressor/motor speed: approximately 1400 RPM (varies with input voltage)
- Helium charge pressure: 550 psig
- Motor power: 60 watts maximum
- Voltage: 18.5 ± 0.5 VDC
- Starting torque: 75 in-oz.

2.4 Expander Assembly

The expander assembly (Figure 5) houses the free-floating displacer assembly within a thin-walled stainless steel cylinder having a cold tip at one end for cooling the detector element. The displacer assembly within the expander contains the regenerative heat exchanger medium consisting of small diameter nickel spheres packed to form a cylindrical matrix. The displacer assembly has attached to its warm end a small drive piston which serves as the driving element to move the displacer assembly back and forth in response to the cyclic pressure variations of the compressor. The displacer is sealed and guided by close tolerance mating parts as well as a spring loaded lip seal. A connecting fitting attached to the expander housing joins the expander assembly to the compressor via the interconnecting gas line shown in Figure 5.

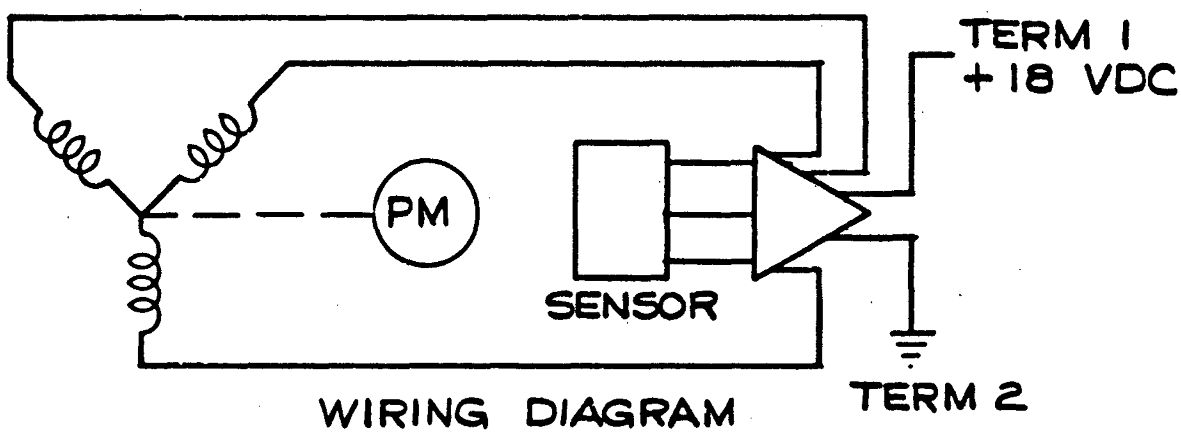


FIGURE 4. WIRING DIAGRAM

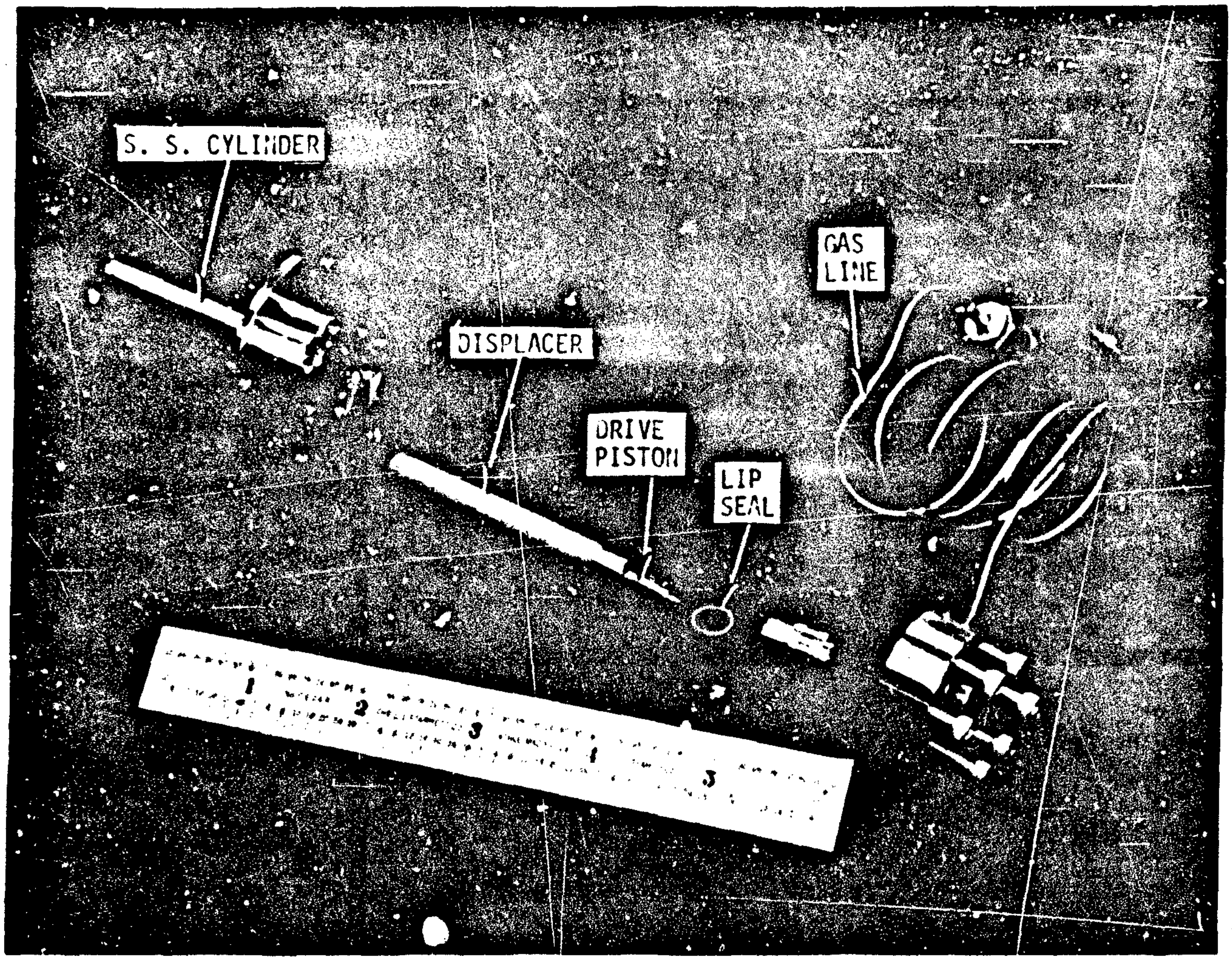


FIGURE 5. EXPANDER ASSEMBLY

2.5 Key Expander Parameters

- Displacer diameter: 0.300 inch
- Displacer stroke length: 0.070-0.080 inches
- Displacer travel frequency: approximately 1400 cpm

2.6 Interconnecting Line

A stainless steel capilliary interconnecting supply line pneumatically connects the compressor unit to the expander assembly. This line, approximately 24 inches in length, allows the expander assembly to be located remotely from the compressor unit. This design feature is important in the military applications where envelope space in the area of the expander is very limited.

2.7 Cryogenic Cooler Profile

The compressor, expander assembly, and interconnecting line were designed and configured to fit within required space envelope constraints. Figure 6 shows these profile dimensions.

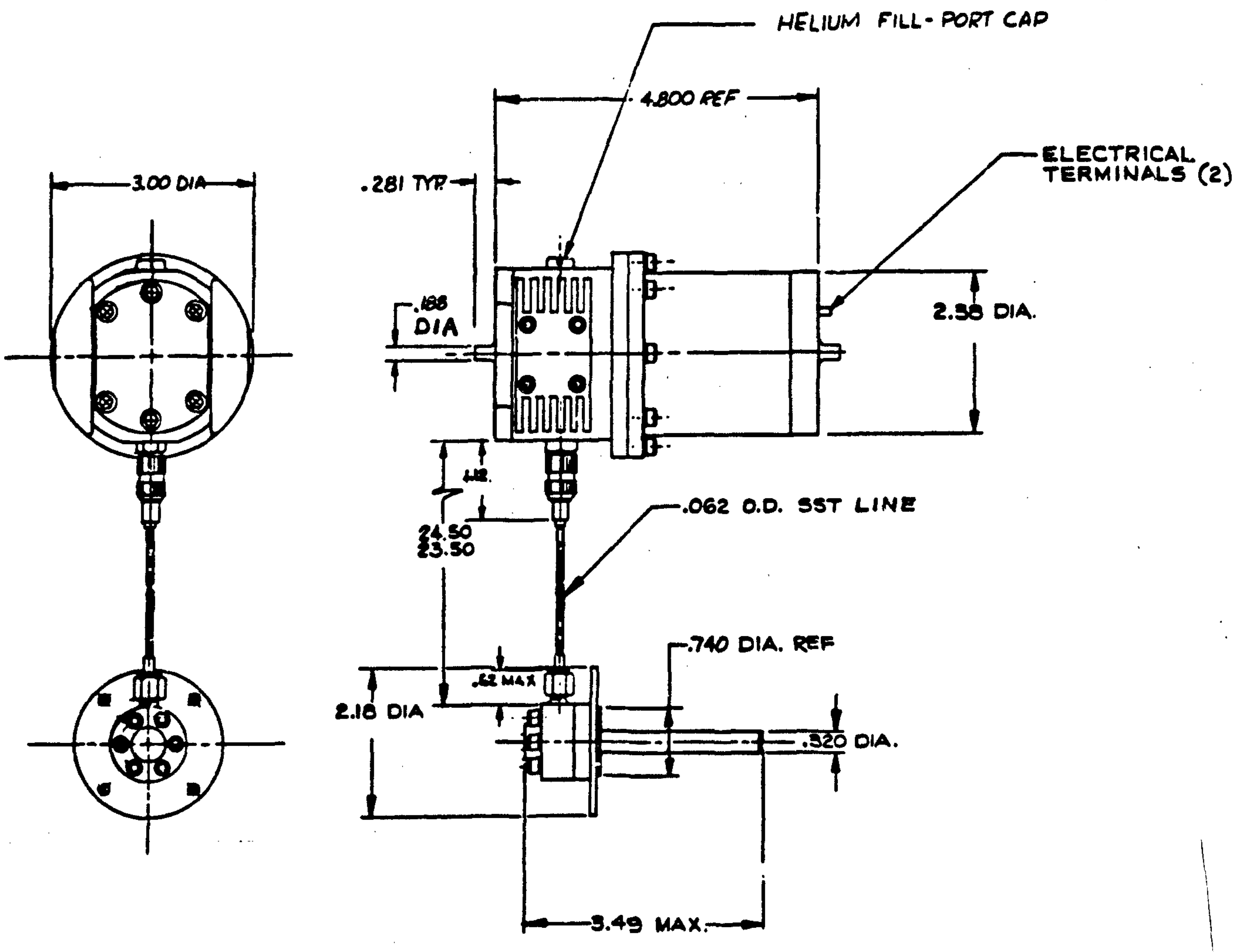


FIGURE 6. 1.0 WATT COOLER ASSEMBLY - ENVELOPE DIMENSIONS

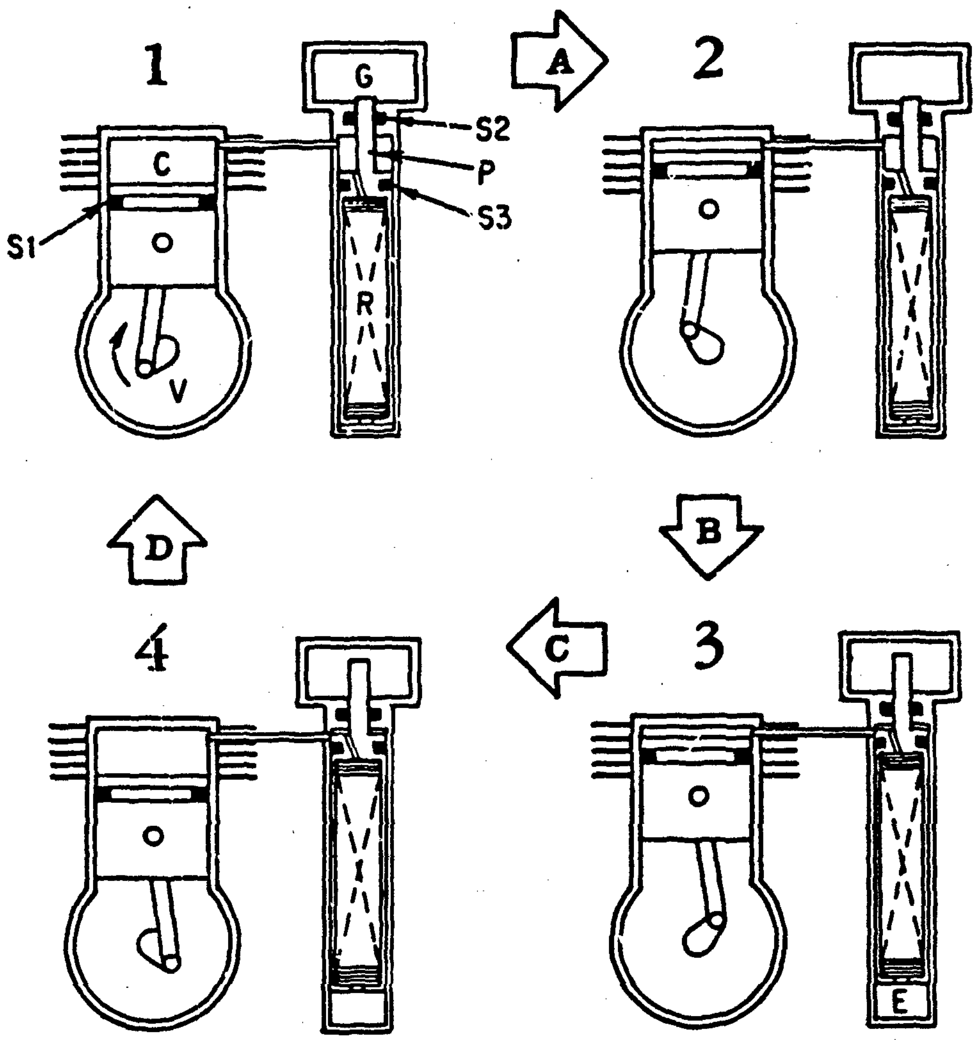
3.0 THEORY OF OPERATION

The CTI-CRYOGENICS 1.0 Watt Split-Stirling Cryocooler is a closed cycle, semi-hermetically sealed system designed to provide continuous cooling at a temperature of 80K or better to an infrared detector array.

In the Split-Stirling system, the compressor, with its motor and crankcase, comprises one package while the expander comprises a second package and the two are interconnected by a single gas line. This arrangement overcomes the principal objection to the integral Stirling design, since it separates the compressor from the expander, thus removing the bulk, heat, and vibration of the compressor from the sensitive region of the detector or other cooled device.

Reciprocating motion for the displacer is provided by a compact pneumatic drive wherein the sinusoidal pressure fluctuations generated by the compressor provide the necessary forces to drive the displacer up and down in proper timed relationship with the compressor. Since the system uses no valves, the gas line constitutes an important void volume. Because of the added void volume associated with the interconnecting line, and the lack of a direct mechanical linkage between the displacer and compressor, the Split-Stirling Cooler is somewhat less efficient than the corresponding one-piece Stirling.

The semi-hermetically sealed helium gas charge within the Split-Stirling system may be conveniently considered as divided into three volumes (see Figure 7): the crankcase volume V, the working volume, and the gas spring volume G. The crankcase volume is the major gas volume in the system since it surrounds the drive motor, crank drive, and space below the compressor piston. The working volume consists of the compression space C, the interconnecting gas line volume, and all the internal voids in the cold finger (i.e., spaces above and below the displacer, voids in the regenerator matrix R, etc.).



COLD END EXPANSION SPACE P-V DIAGRAM

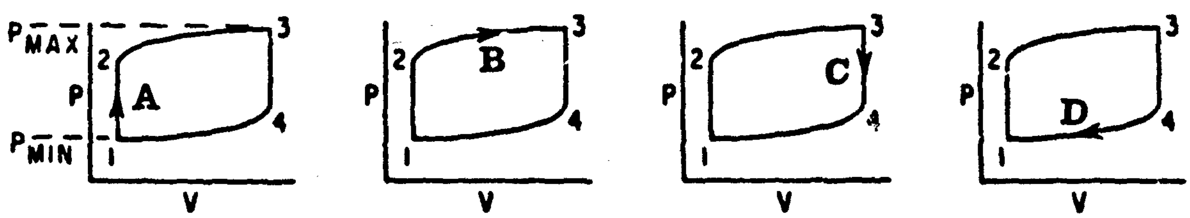


FIGURE 7. SPLIT-STIRLING CYCLE CRYOCOOLER

The crankcase volume V, is isolated from the working volume by the compressor piston seal S1. The gas spring volume G, is isolated from the working volume by the drive piston seal S2. Since the swept volume of the compressor piston (compression space C) constitutes the major portion of the working volume, it follows that moving the piston up and down in a sinusoidal manner will generate a sinusoidally varying pressure throughout the entire working volume. The gas spring volume and the crankcase volume will both stabilize at a pressure level essentially equal to the average value of the fluctuating working volume pressure (due to minute gas leakage past the compressor piston and drive piston seals).

The cycle may be described by tracing the flow of gas from the compression space C through the interconnecting line and the regenerator R to the expansion space E at the tip of the cold finger. The regenerator R is located inside the reciprocating displacer, and consists of a porous matrix of nickel spheres having a large heat capacity that maintains a temperature gradient along it - typically from 300K (80°F) to 77K (-321°F). Helium gas cools from 300K to 77K as it passes through the regenerator matrix from the compressor to the expander and warms from 77K to 300K on the return pass.

Operation of the Split-Stirling cycle can best be understood by referring to Figure 7 and the P-V diagram and describing the various events as they occur in a typical cycle.

3.1 Phase A (Process 1-2)

Assume the displacer to be at the lower (cold) end of the cold finger with the compressor piston moving upward toward top dead center. This causes the working gas pressure to rise from P (min) toward P (max) - thus creating a pressure difference across the drive piston P, which overcomes the friction of the displacer seal S3 and forces the drive piston (and displacer) upward.

3.2 Phase B (Process 2-3)

As the displacer moves from the cold end, high pressure ambient temperature working gas is forced through the regenerator into the expansion space E, being cooled from 300K to 77K as the regenerator absorbs heat from the gas.

3.3 Phase C (Process 3-4)

The compressor piston now moves downward and working pressure falls, allowing the high pressure helium in the cold volume to expand (Process 3-4) and cool further. It is this expansion cooling process which maintains the temperature gradient of 300K to 77K over the length of the regenerator.

3.4 Phase D (Process 4-1)

As the working gas pressure falls below the pressure in the gas spring volume G, the drive piston is forced downward which forces the remaining cold, low-pressure working gas from the cold volume, out through the regenerator (where it picks up heat from the nickel sphere matrix and warms from 77K to 300K) thus completing the cycle (Process 4-1).

4.0 PERFORMANCE

The purpose of this contract was to design, fabricate and test a high performance closed cycle 1.0 watt Split-Stirling Cryogenic Cooler for cooling infrared detectors on gimballed platforms. Because of the sensitivity of the mounting area, the Cooler must operate with minimum vibration and acoustic noise; it must provide dependable performance through the environmental extremes. Table I shows the specific performance requirements that the cooler is designed to meet.

TABLE I. COOLER PERFORMANCE REQUIREMENTS

° REFRIGERATION TYPE	- SPLIT-STIRLING
° REFRIGERATION CAPACITY	- 1.0 W AT 77°F (25°C) AMBIENT - 0.75 W AT -40°F (-40°C) AND 131°F (55°C) AMBIENT
° COOLDOWN TIME TO 100K (WITH 11 GRAM EQUIVALENT MASS)	- 10 MINUTES AT 77°F (25°C) AMBIENT
° COOLDOWN TIME TO 80K (WITH 11.2 GRAM EQUIVALENT MASS)	- 15 MINUTES AT 77°F (25°C) AMBIENT
° INPUT POWER	- 60 W, 18.5 $\pm$ 0.5 VDC STEADY STATE
° WEIGHT	- 4 LBS. MAXIMUM
° AMBIENT TEMPERATURE LIMITS OPERATING	- -40°F (-40°C) TO 131°F (55°C)
° TRANSFER LINE LENGTH	- 24 INCHES

TABLE I. COOLER PERFORMANCE REQUIREMENTS (CONTINUED)

• MILITARY SPECIFICATIONS	- MIL-STD-810: • TEMPERATURE - SHOCK • HIGH-LOW TEMPERATURE • MECHANICAL SHOCK (100 G'S AT 11 MILLISECONDS) • SINUSOIDAL VIBRATION (5 G'S, 20-2000 HZ) - MIL-STD-781B • 1000 HOURS MTBF
• CONTRACT SPECIFICATIONS	- SOUND PRESSURE AT 5 METERS 49.5 TO 26.5 (DB) OVER 125-11,200 (HZ) - INDUCED VIBRATION 15. IN-OZ. MAJOR AXIS, 4 IN-OZ. OTHER AXES
• COMPRESSOR MOTOR	- LOCKED ROTOR CURRENT: 10 AMPS - MAX STARTING CURRENT: 8.5 AMPS - MAX STARTING TIME: 50 MILLISECONDS

5.0 TEST FACILITIES AND EQUIPMENT

All testing for the 1.0 Watt Split-Stirling High Performance Cryogenic Coolers was done at one of the following three places, as noted, with the support equipment identified.

5.1 CTI-CRYOGENICS, 266 Second Avenue, Waltham, MA 02254

5.1.1 Test Performed

a. 1000 hours MTBF
b. Performance Test
c. Acceptance Tests

5.1.2 Test Equipment Used

Instrumentation	Manufacturer	Model No.
3 Input Strip Chart Recorder	Esterline Angus	MS413B H82
Environmental Chamber	Associated	SK3108
Micro-Pro 1000	Watlow	93-00-03
Microprocessor	Esterline Angus	PD-2064
Ionization Gauge Control	VEECO	RG-830
Digital Readouts	Analogic	AN2553LP
Vacuum System	CTI-CRYOGENICS	CRYO-TORR(R) 7
D.C. Power Supplies	Power-One	E5-18
Diodes	Lakeshore	DT-500 CU-DRC-B
50 Ohm Heater Mounted on a Cu. Mass	CTI-CRYOGENICS	---

5.2 AVCO Environmental Testing Services, 201 Lowell Street, Wilmington, MA

5.2.1 Test Performed

a. Sinusoidal Vibration
b. Shock Tests

5.2.2 Test Equipment Used

Instrumentation	Manufacturer	Model No.
Shock Machine	AVCO	SM110
Accelerometer	Endevco	2213C
Cathode Follower	Calidyne	4000R
Bandpass Filter	Krohn-Hite	335
Oscilloscope	Tektronix	535A
Calibrator	Ballantine	420
Vibration System #1		
Shaker	MB	C25HB
Sine Control	UD	M100
Accelerometer	Endevco	2213C

5.3 Bolt, Beranek and Newman, Inc., 50 Moulton Street, Cambridge, MA

5.3.1 Test Performed

a. Self-Induced Vibration
b. Acoustic Noise

5.3.2 Test Equipment Used

Instrumentation	Manufacturer	Model No.
Condenser Microphone	Bruel & Kjaer	4133
Preamplifier	GenRad	1560-P42
Sound Level Meter	Bruel & Kjaer	2203

Instrumentation	Manufacturer	Model No.
Amplifier	Ithaco	453
Pistonphone Calibrator	Bruel & Kjaer	4220
Accelerometer	Bolt Beranek and Newman Inc.	501
Amplifier	Ithaco	453
Vibration Calibrator	GenRad	1557A
FFT Computing Spectrum Analyzer	Nicolet Scientific	446A
Sum-Difference Amplifier	Bolt Beranek and Newman, Inc.	--

6.0 TEST PROGRAM

The test program for the six cryogenic coolers consisted of the environmental and life testing necessary to qualify the design and evaluate its strengths and weaknesses. A copy of the CTI-CRYOGENICS' Performance Test Plan, No. A3543 600, is presented in Appendix V. It was planned that of the six coolers, three would be used for the Life Testing Program. Throughout the test program the coolers will be identified and discussed by their serial numbers: S/N 001, S/N 002, S/N 003, S/N 004, S/N 005 and S/N 006. The testing, as conducted, fell into one of three major categories and their subdivisions as noted:

Natural Environmental Tests

- Temperature - Shock
- High Temperature
- Low Temperature
- Performance Tests

Dynamic Environmental Tests

- Mechanical Shock
- Vibration
- Self-Induced Vibration
- Acoustics

Life Tests

- 1000 Hours MTBF

6.1 Natural Environmental Tests

6.1.1 Temperature Shock. Two cryogenic coolers, S/N 002 and S/N 003, were temperature shock tested from a stabilized temperature of +68.3°C to -54°C several times in accordance with the requirements of MIL-STD-810B, Method 503. Baseline cooler operating performance data, before and after the temperature shock test, showed no out of specification performanc. as a result of the shock test. This data is summarized on the performance curves as shown in Figures 8 and 9.

6.1.2 High Temperature. Two cryogenic coolers, S/N 002 and S/N 003, were cycled per Procedure II of MIL-STD-810B at the required temperature of Steps 4 and 5. The highest operating temperature was 71°C. Steps 1 and 8 were repeated except that the temperature of Step 2 (highest temperature) was +71°C, the length of time during Step 3 was 30 minutes, and the temperature of Steps 4 and 5 (highest operating temperature) was +71°C. A comparison of performance operating data before and after the high temperature test showed no out of specification conditions as a result of the test. This data is summaried on the performance curves as shown in Figures 10 and 11.

6.1.3 Low Temperature. Two cryogenic coolers, S/N 002 and S/N 003, were tested per test Method 502, Procedure I of MIL-STD-810B with the storage temperature (Step 2) set for -52°C and maintained until temperature stabilization of the cooler was reached. Low operating temperature (Step 4) was -54°C. A comparison of operating results before and after the low temperature test showed no out of specification performance as a result of the test. This data is summarized on the performance curves as shown in Figures 12 and 13.

6.1.4 Performance Tests. One cryogenic cooler, S/N 001, was put through operational tests using the spectrum of temperature limits from 70°F, 131°F and -40°F. At each temperature reading the cooler was operated at no load and 1 watt load conditions as well as cooldown time to 80K. At each temperature the load carrying level was better than specification requirements. As a further evaluation of the coolers operating capability, it was run at -65°F. The performance data is summarized on the performance curves as shown in Figure 14.

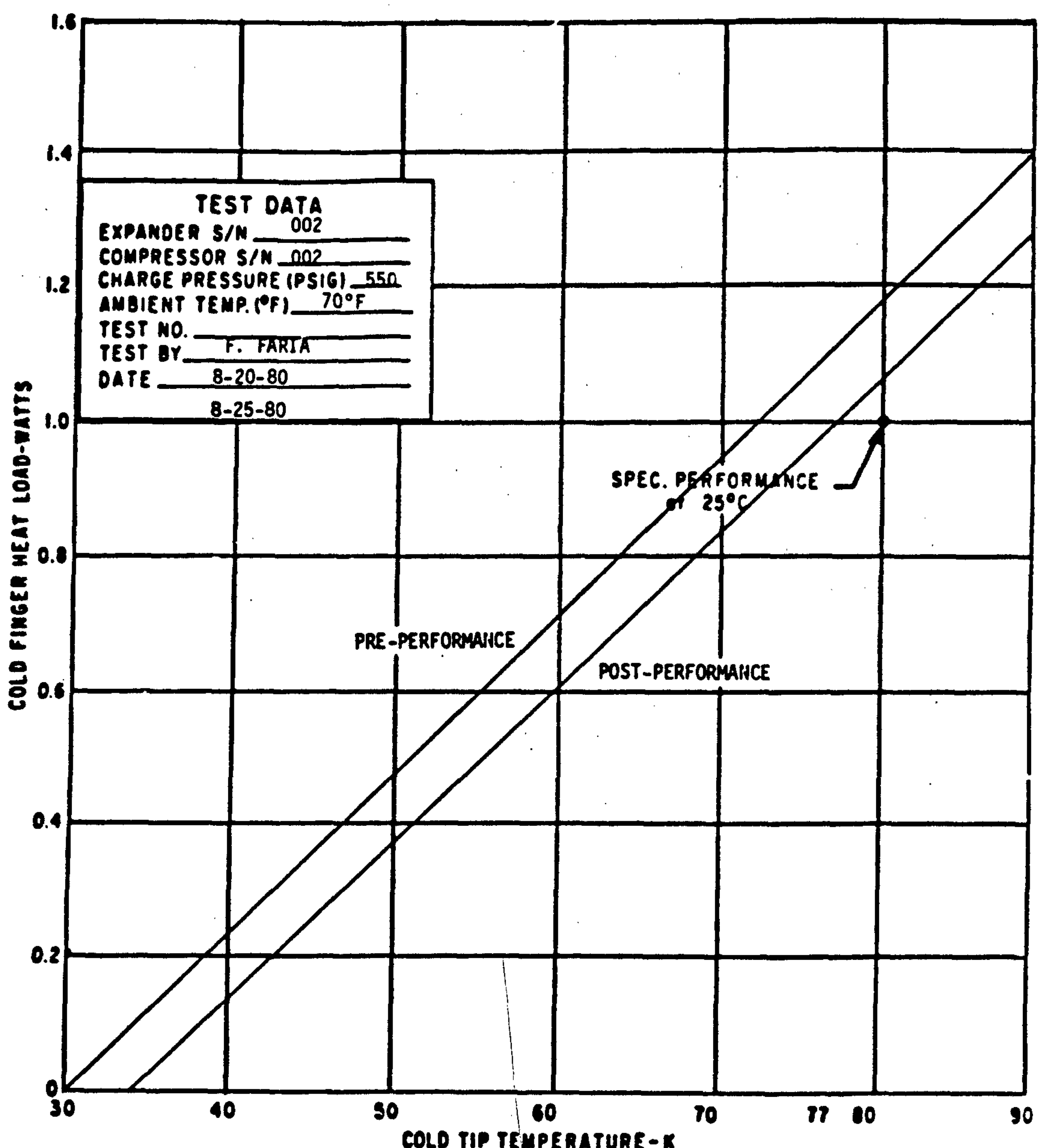


FIGURE 8. TEMPERATURE-SHOCK COMPARISON PERFORMANCE DATA, S/N 002

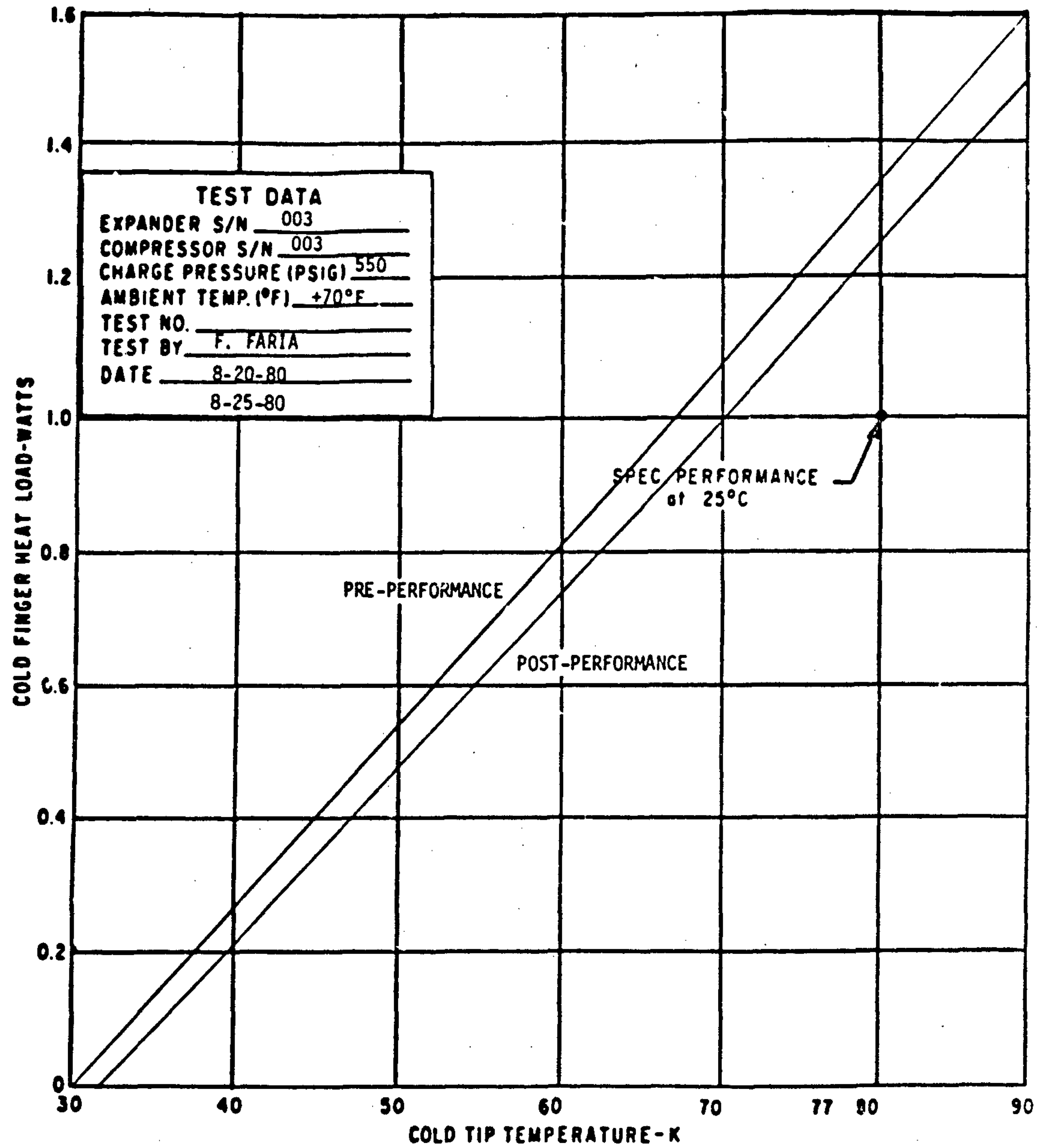


FIGURE 9. TEMPERATURE-SHOCK COMPARISON PERFORMANCE DATA, S/N 003

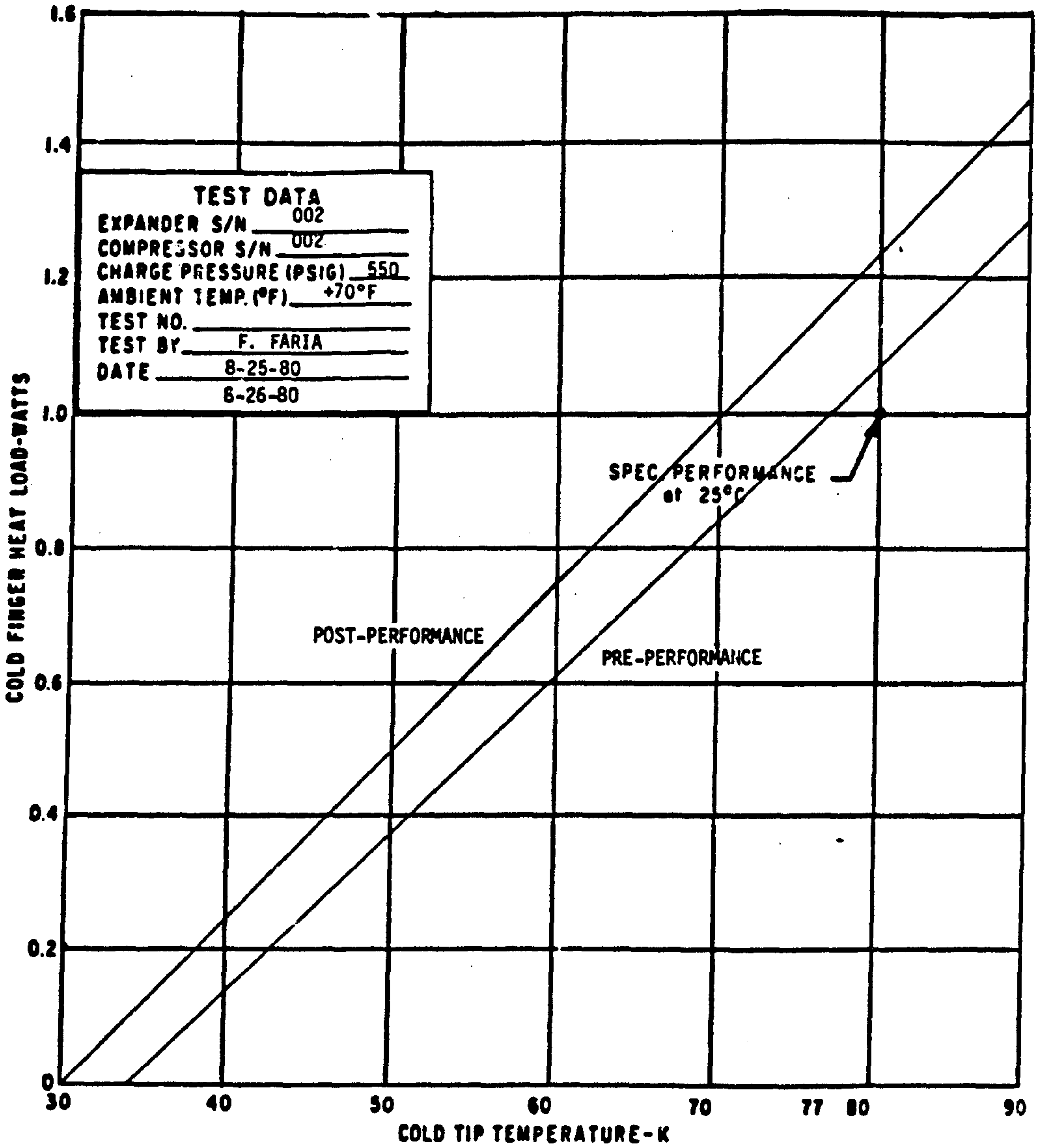


FIGURE 10. HIGH TEMPERATURE TEST COMPARISON PERFORMANCE DATA, S/N 002

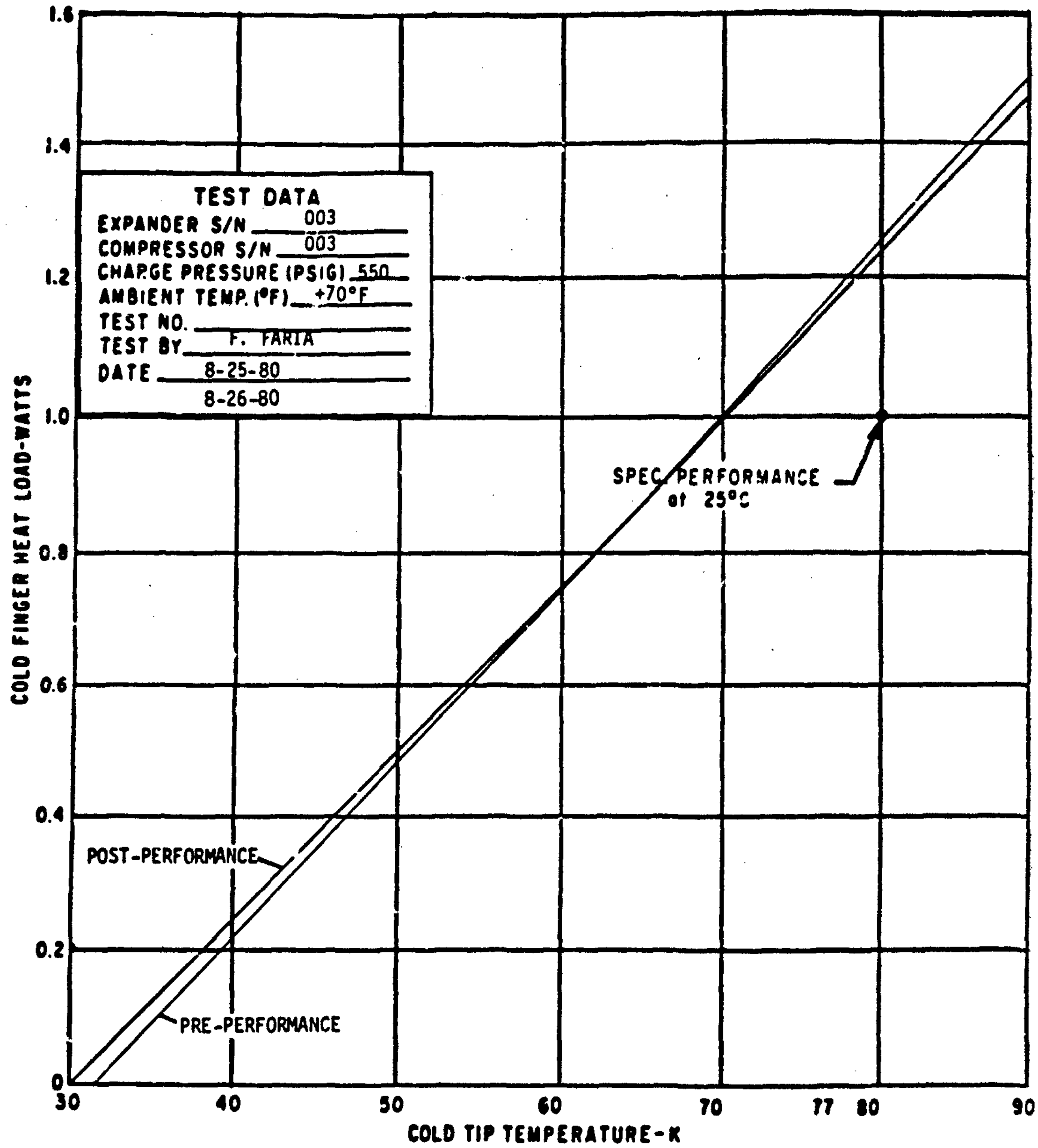


FIGURE 11. HIGH TEMPERATURE TEST COMPARISON PERFORMANCE DATA, S/N 003

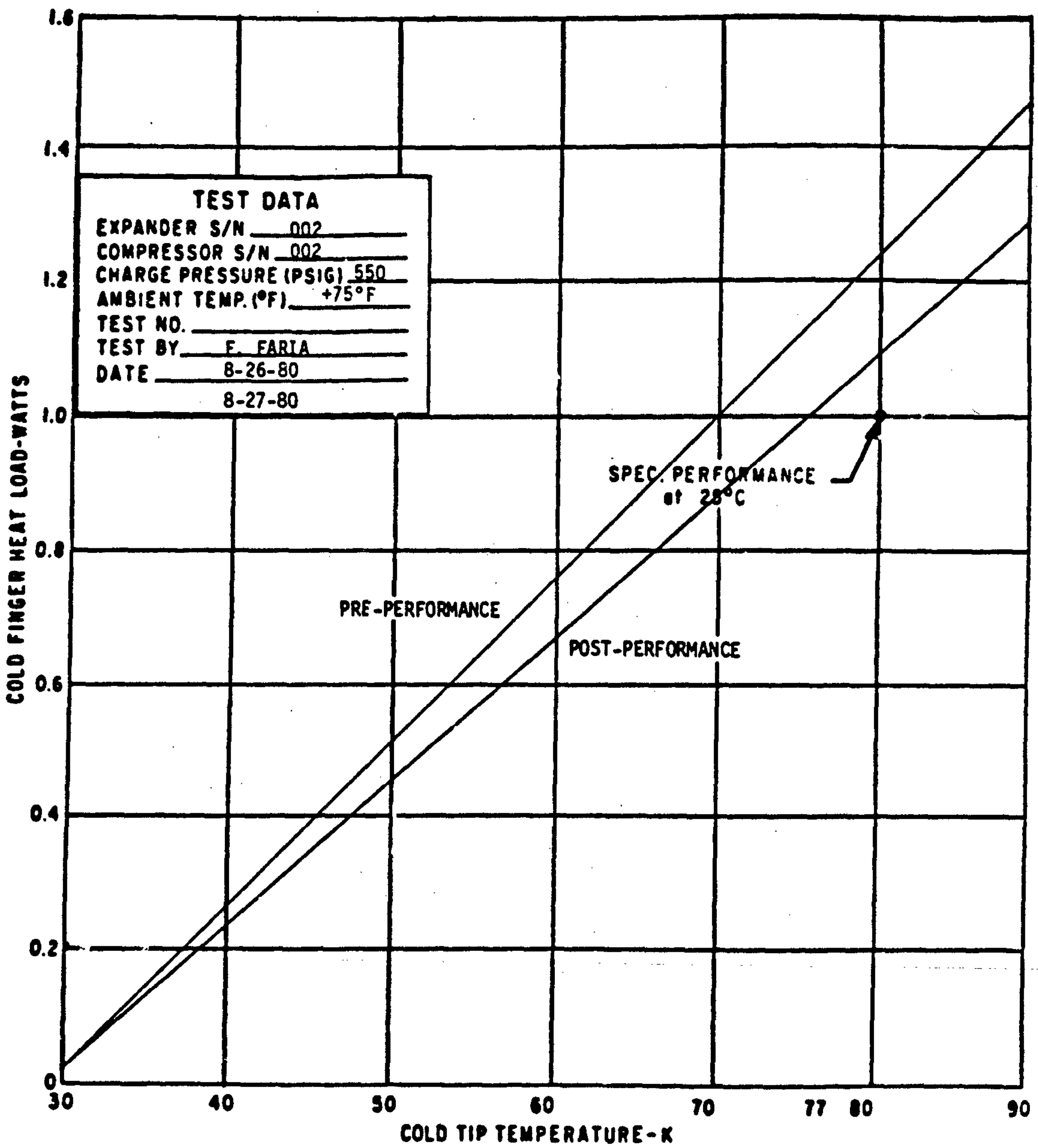


FIGURE 12. LOW TEMPERATURE TEST COMPARISON PERFORMANCE DATA, S/N 002

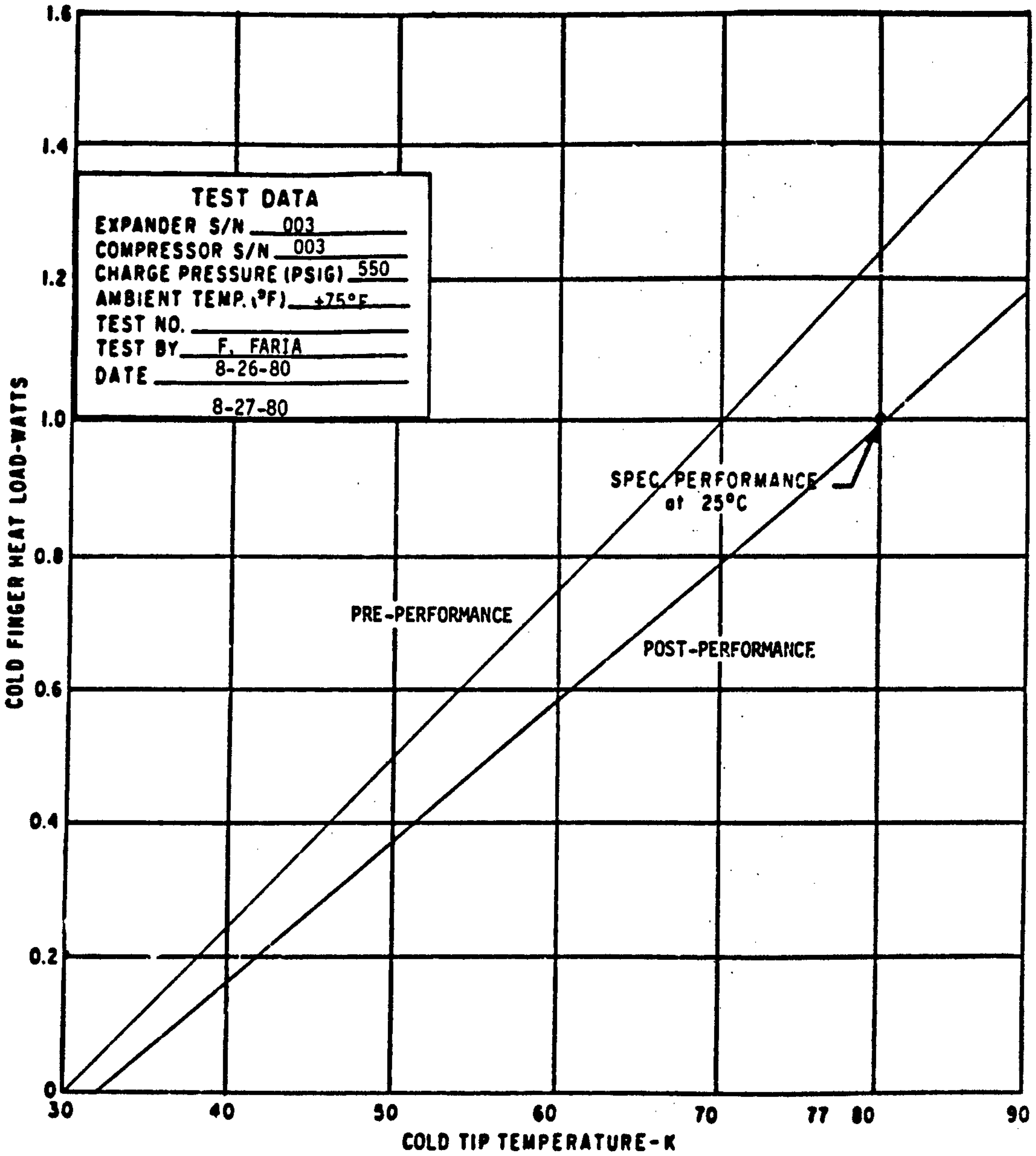
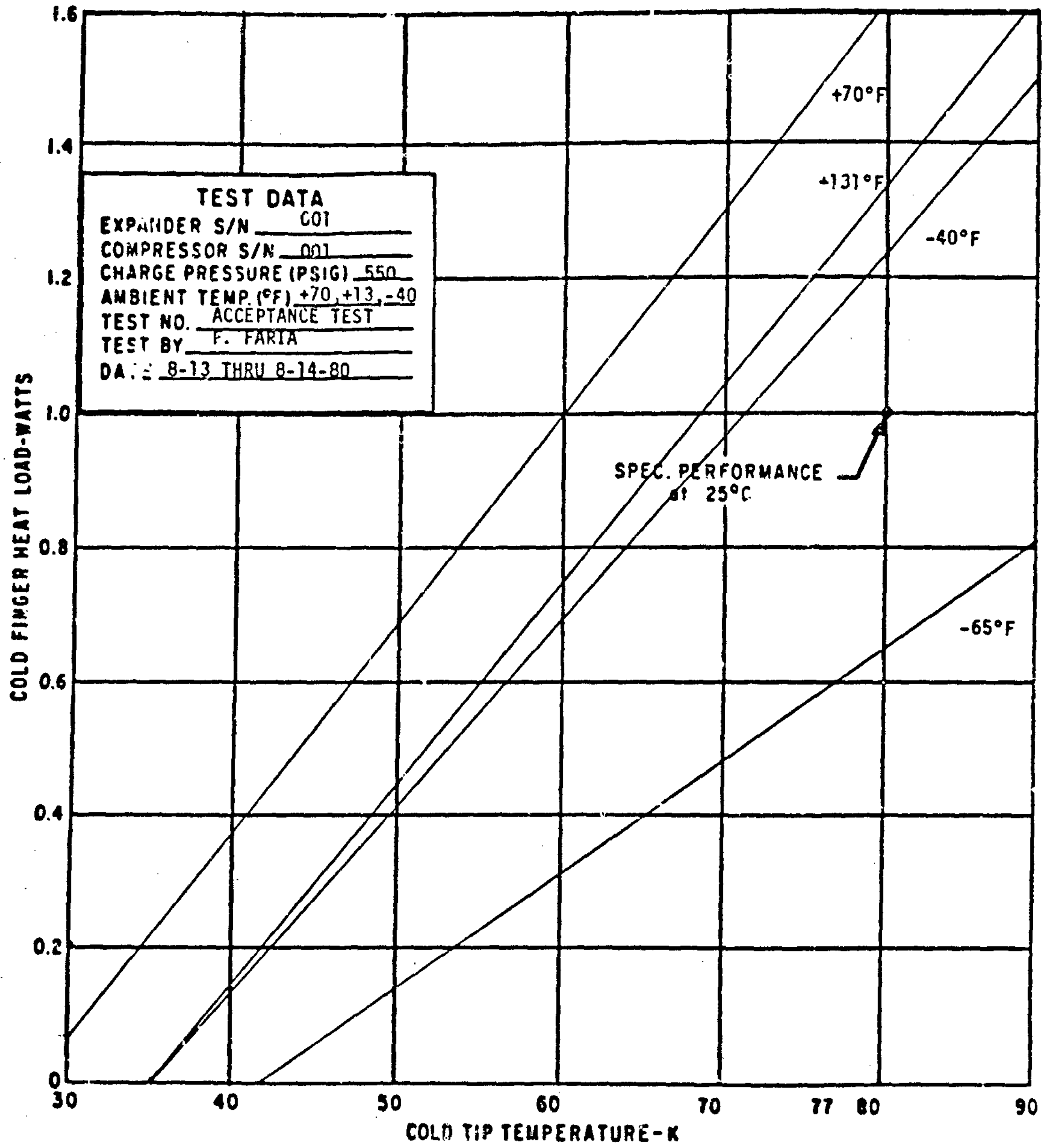


FIGURE 13. LOW TEMPERATURE TEST COMPARISON PERFORMANCE DATA, S/N 003



S/N 001 Performance at +70°F, +131°F, -40°F, and -65°F

FIGURE 14. PERFORMANCE TEST DATA

6.2 Dynamic Environmental Test

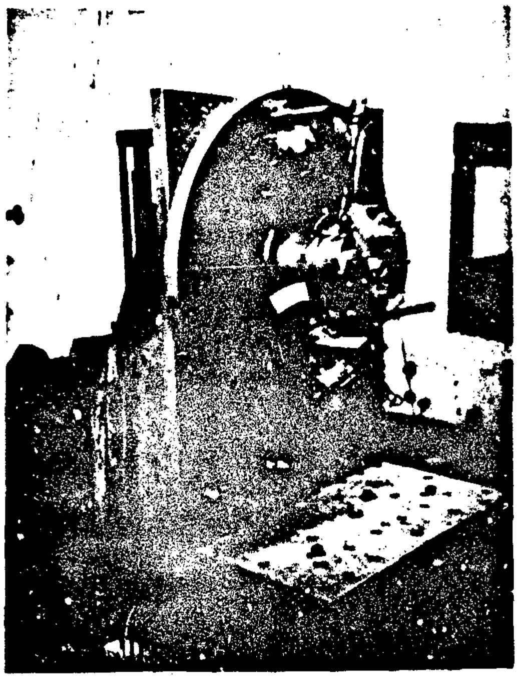
6.2.1 Mechanical Shock. Two cryogenic coolers, S/N 002 and S/N 003, were subjected to the high intensity shock tests of MIL-STD-810B, Method 516.1 Procedure IV per Figure 516.1-1. Each cooler received a total of 12 shocks; 2 in each direction along each of its 3 mutually perpendicular axes at a level of 100 G for 11 milliseconds.

AVCO Environmental Testing Services of Wilmington, MA performed these shock tests under direction from CTI-CRYOGENICS. Figure 15 shows coolers S/N 002 and S/N 003 securely mounted to a SM110 shock machine in different attitudes for shock testing along the coolers respective major axes. Figure 16 shows a series of typical shock patterns recorded on and photographed from an oscilloscope.

In addition to Procedure IV, Procedure V, of MIL-STD-810B, bench handling shock tests were conducted on both cooler systems per Method 516.1. After shock test from both IV and V procedures, the coolers were performance tested and found to be within acceptable limits. A summary of the data is shown on the performance curves in Figures 17 and 18.

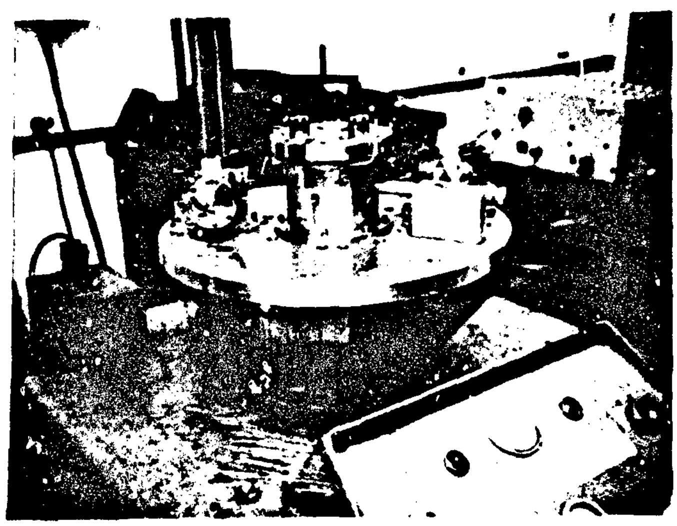
A test certificate of compliance from AVCO Environmental Testing Services for completion of the mechanical shock tests is shown in Appendix I.

6.2.2 Vibration. Two cryogenic coolers, S/N 002 and S/N 003, were subjected to vibration to the conditions of MIL-STD-810B, Method 514.1, Procedure VIII, Figure 514.1-6, Test Level W and Procedure I, Figure 514.1-1, Test Level M. Each cooler was vibrated along its X, Y, and Z axes (per Figure 19), for resonance search, resonance dwells and vibration cycling. This



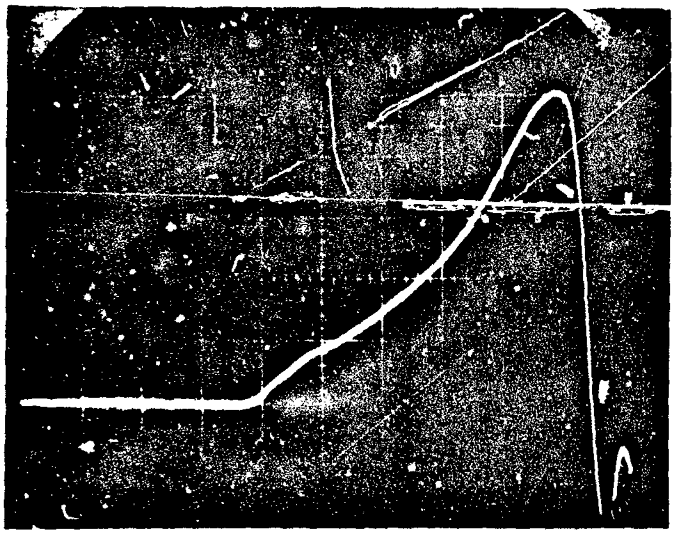
X-AXIS

Y-AXIS

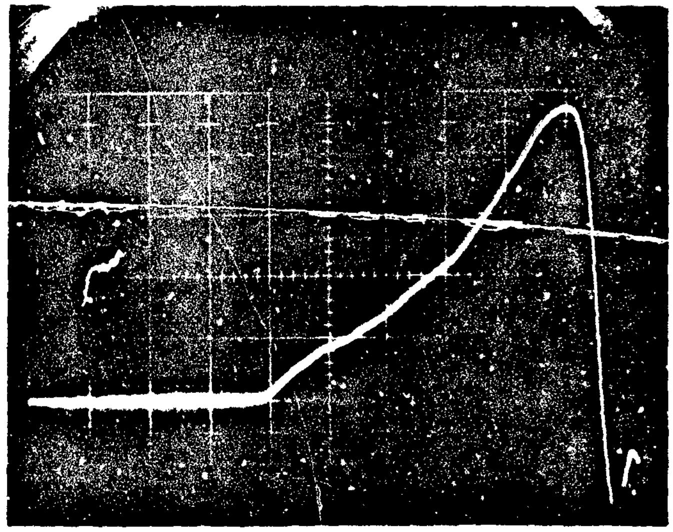


Z-AXIS

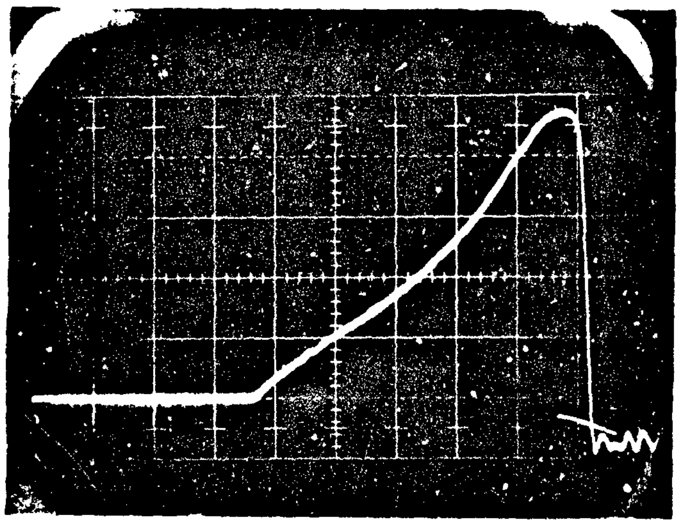
FIGURE 15. SHOCK TEST MOUNTING OF COOLERS S/N 002 AND S/N 003



X-AXIS



Y-AXIS



Z-AXIS

Scale: Scale: 20 g's/cm and 2 ms/cm

FIGURE 16. SHOCK TEST WAVE CURVES

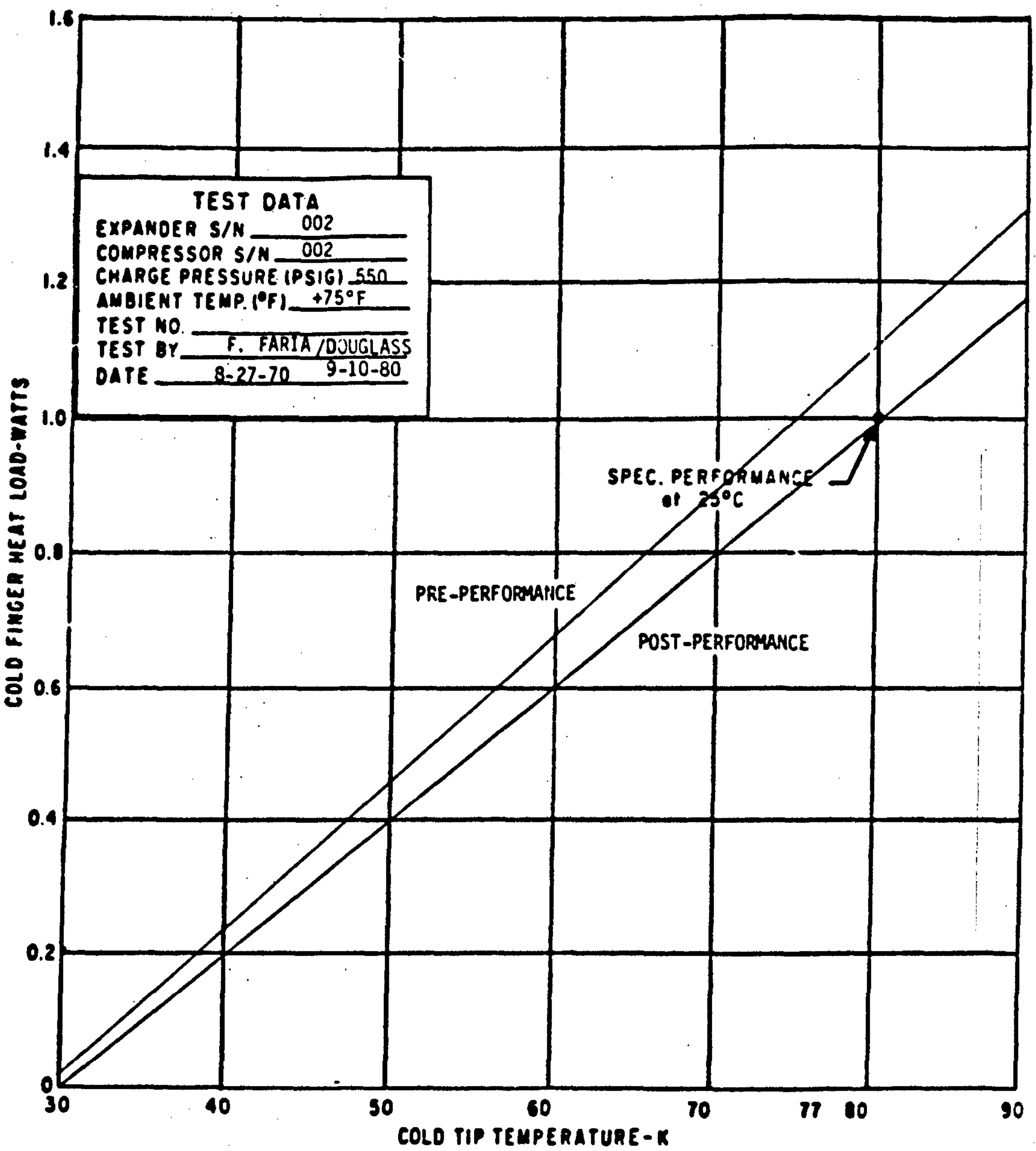
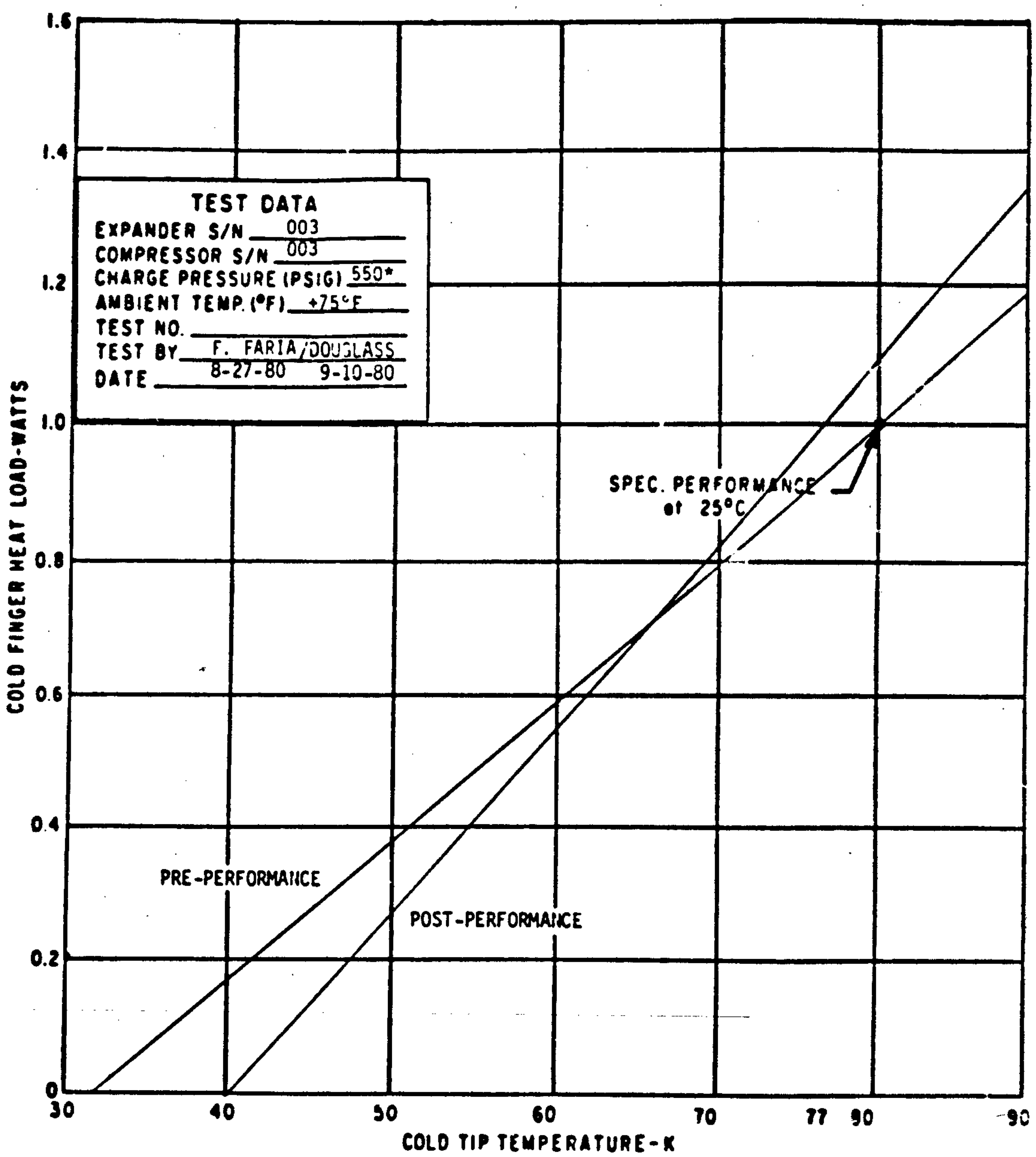


FIGURE 17. MECHANICAL SHOCK TEST COMPARISON PERFORMANCE DATA, S/N 002



*Loss of gas

FIGURE 18. MECHANICAL SHOCK TEST COMPARISON PERFORMANCE DATA, S/N 003

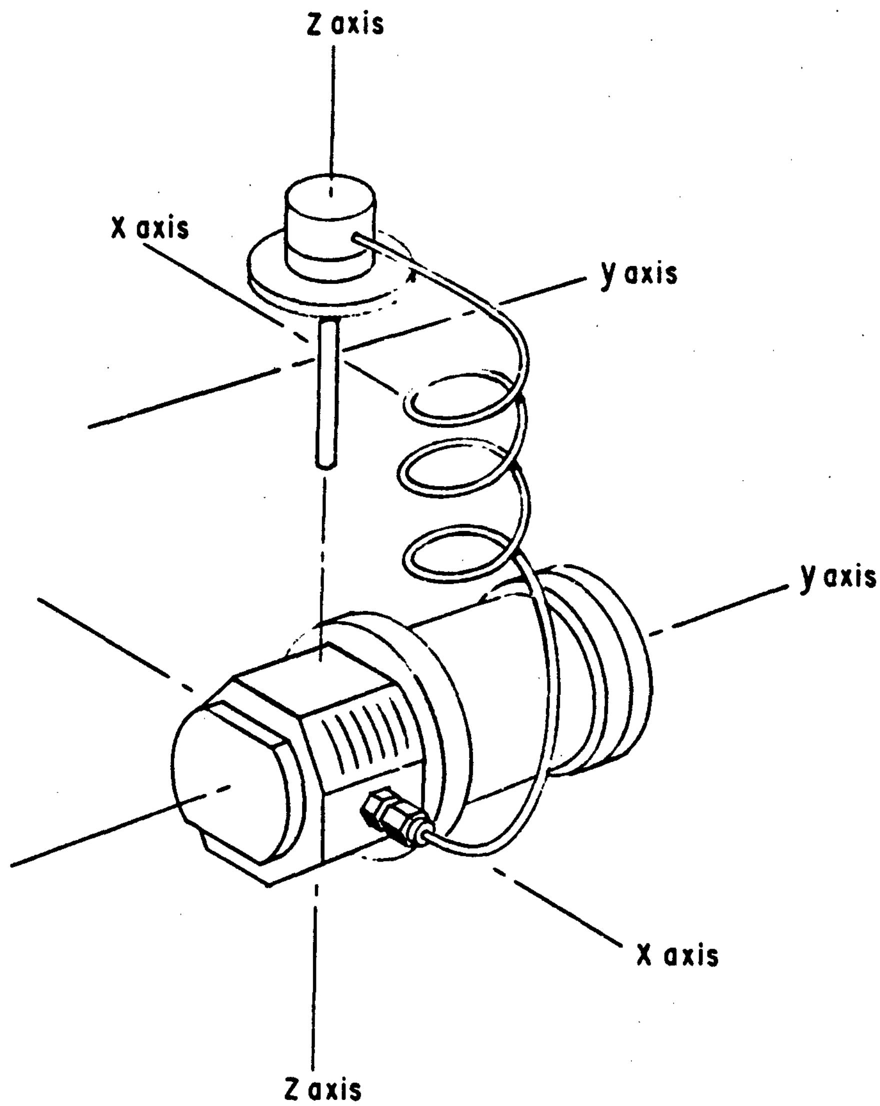


FIGURE 19. VIBRATION AXES DEFINITION

complete procedure was repeated for the Airborne Test Curve M (Figure 20), and the track vehicle test Curve W (Figure 21). During the vibration testing, the cryogenic coolers were operating at room temperature under a 1 watt load.

The actual testing was performed at AVCO Environmental Testing Services in Wilmington, MA, under contract and direction of CTI-CRYOGENICS personnel. Figures 22, 23 and 24 show the test setup, mounting, and location of the two cryogenic coolers in preparation for vibration along each of its three major axes.

The conditions for resonance search, resonant dwell, and cycling dwell vibrations are summarized in the AVCO certification test certificates provided in Appendix II. Cooler Performance test data before and after vibration testing is shown on the curves in Figures 25 and 26.

6.2.3 Self-Induced Vibration. Self-induced vibration testing was subcontracted to the professional testing laboratory of Bolt, Beranek and Newman of Cambridge, MA. Requirements for testing the two cryogenic coolers (S/N 002 and S/N 003) for self-induced vibration output required that the coolers be suspended such that the operating frequency of the cooler was much higher than the natural frequency of the suspension material. A bungee cord suspension system was used as shown in Figure 27. Accelerometers were mounted on the cooler to measure the acceleration on the three major axes and the angular acceleration about each axis. The cryogenic coolers, fully charged, were turned on 15 minutes before measurements were taken. Peak forces derived from the expression F=MA, where F is the peak force, M is the cooler mass, and A is the measured acceleration at a given frequency, were not to exceed 0.4 pounds (semi-amplitude) for any of the first eight (8) harmonics. Peak torque derived from the expression T=I,

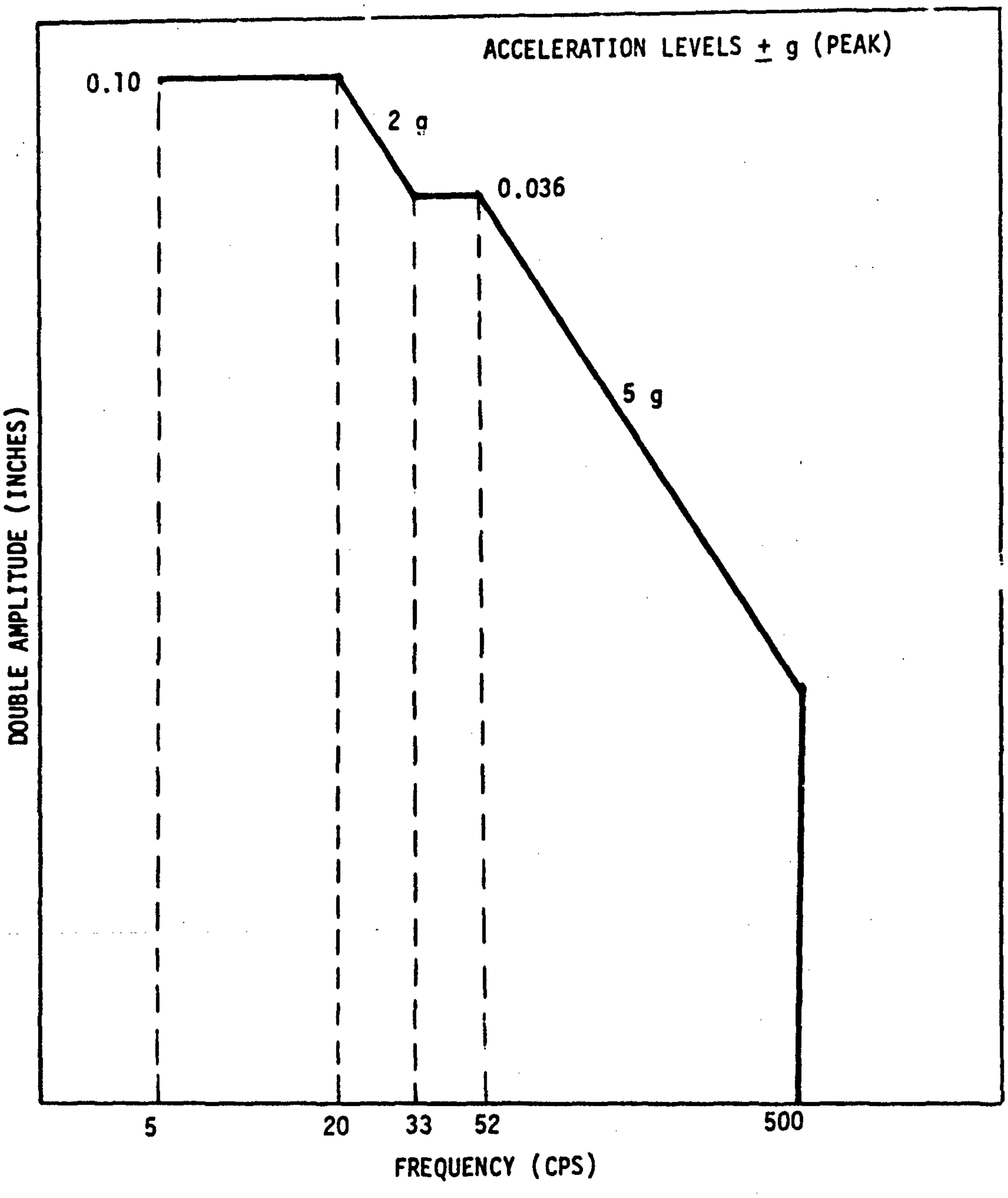


FIGURE 20. VIBRATION TEST CURVE FOR AIRCRAFT VEHICLES

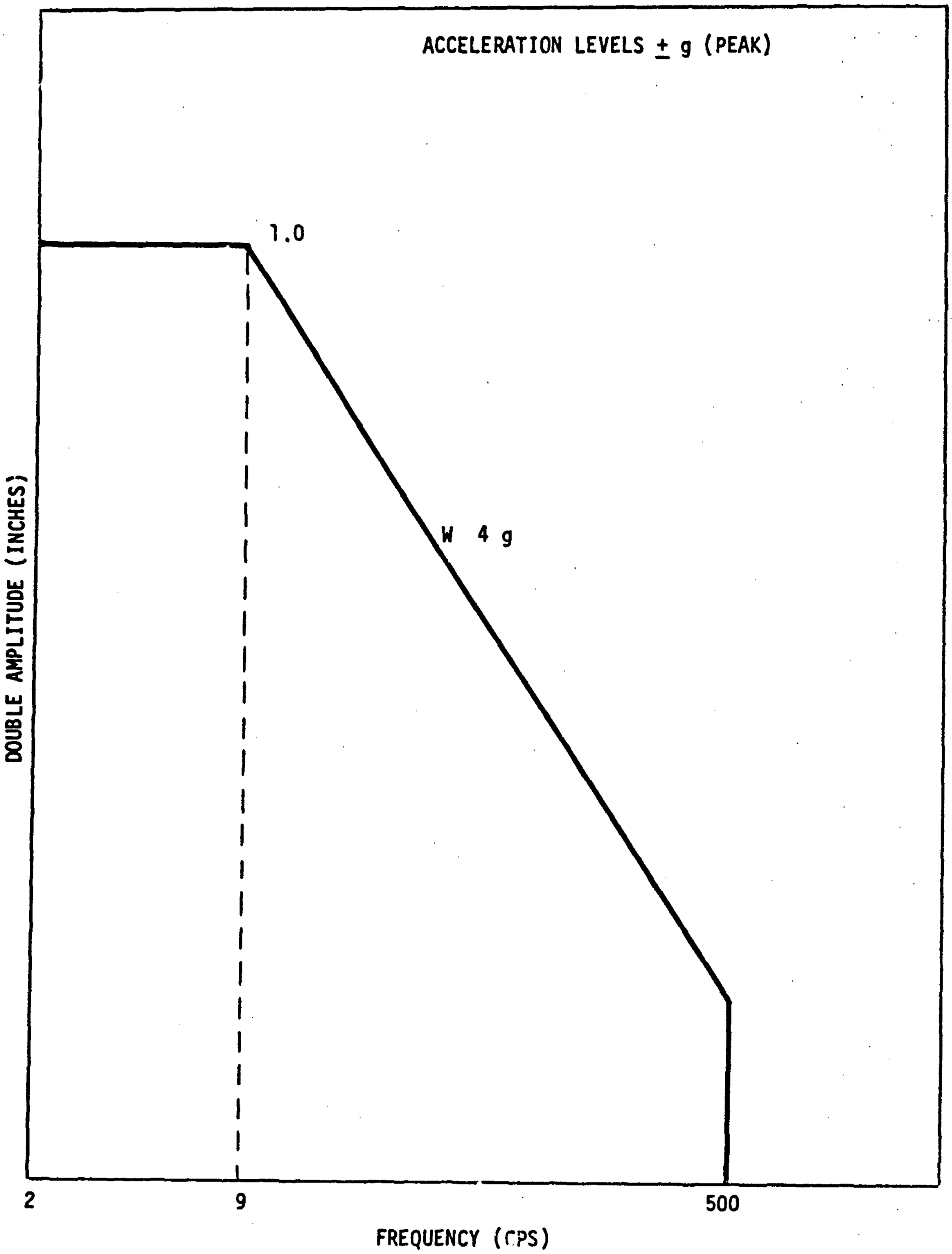


FIGURE 21. VIBRATION TEST CURVES FOR TRACKED VEHICLES

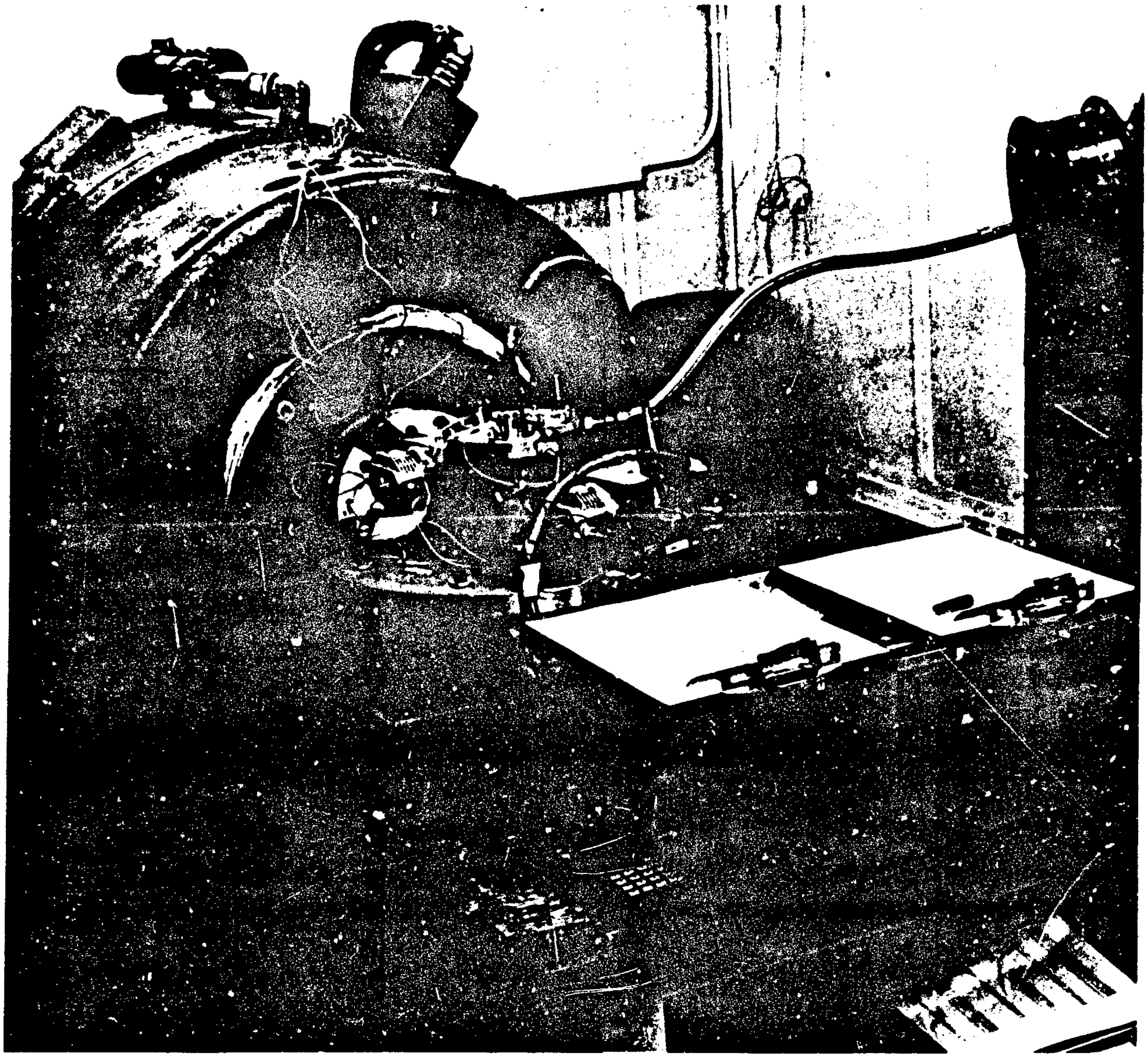


FIGURE 22. VIBRATION TEST SETUP - X AXIS

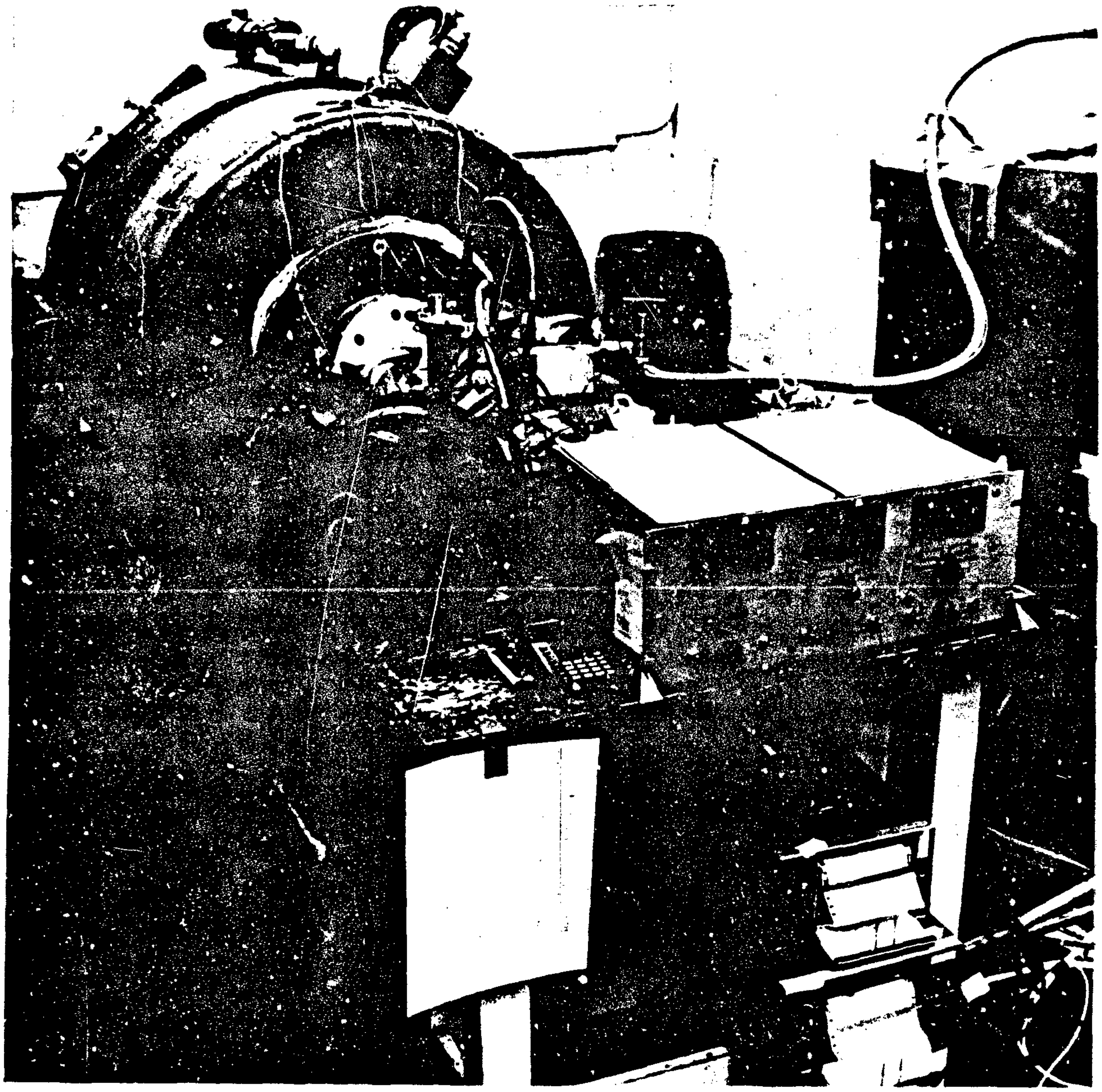


FIGURE 23. VIBRATION TEST SETUP - Y AXIS

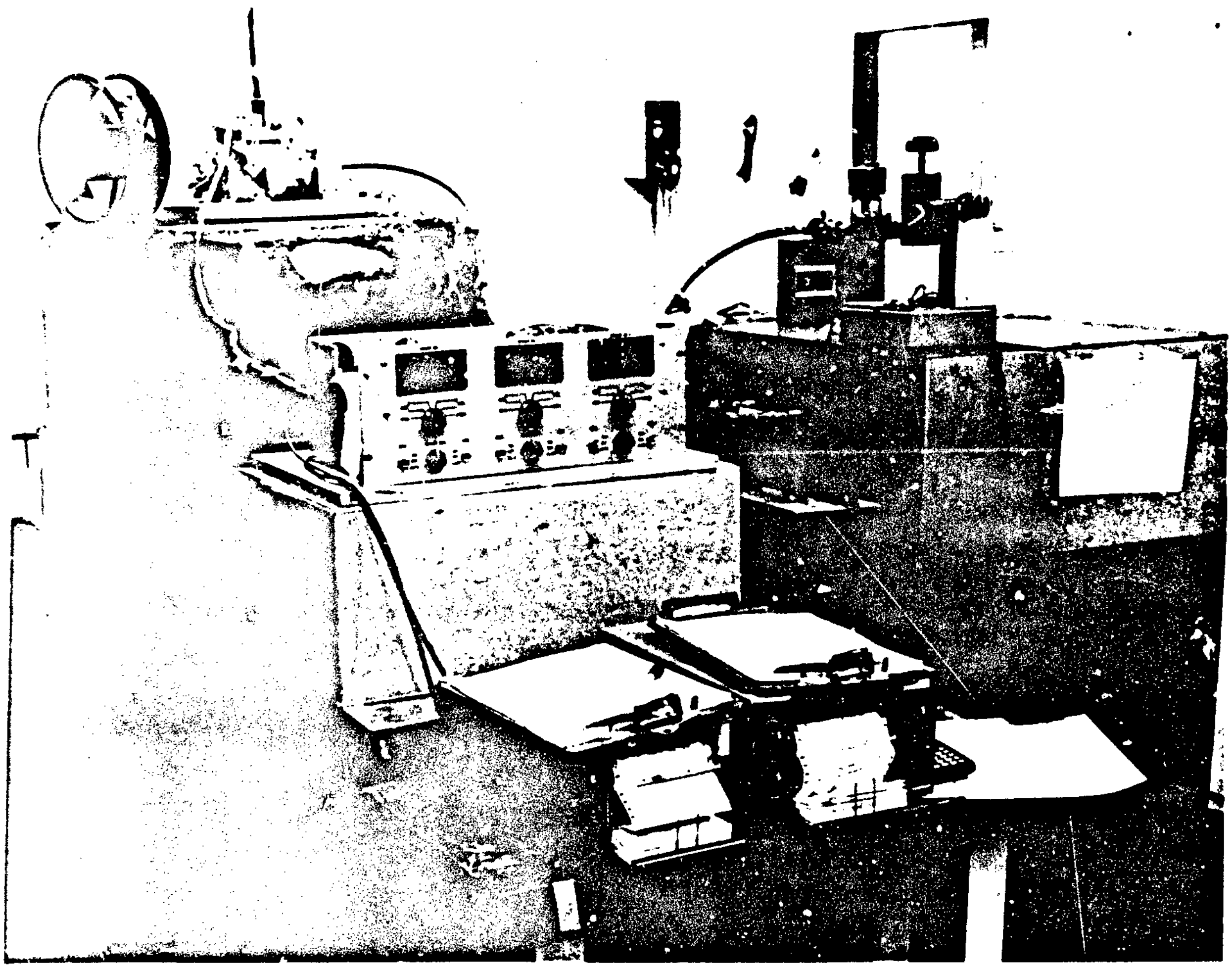


FIGURE 24. VIBRATION TEST SETUP - Z AXIS

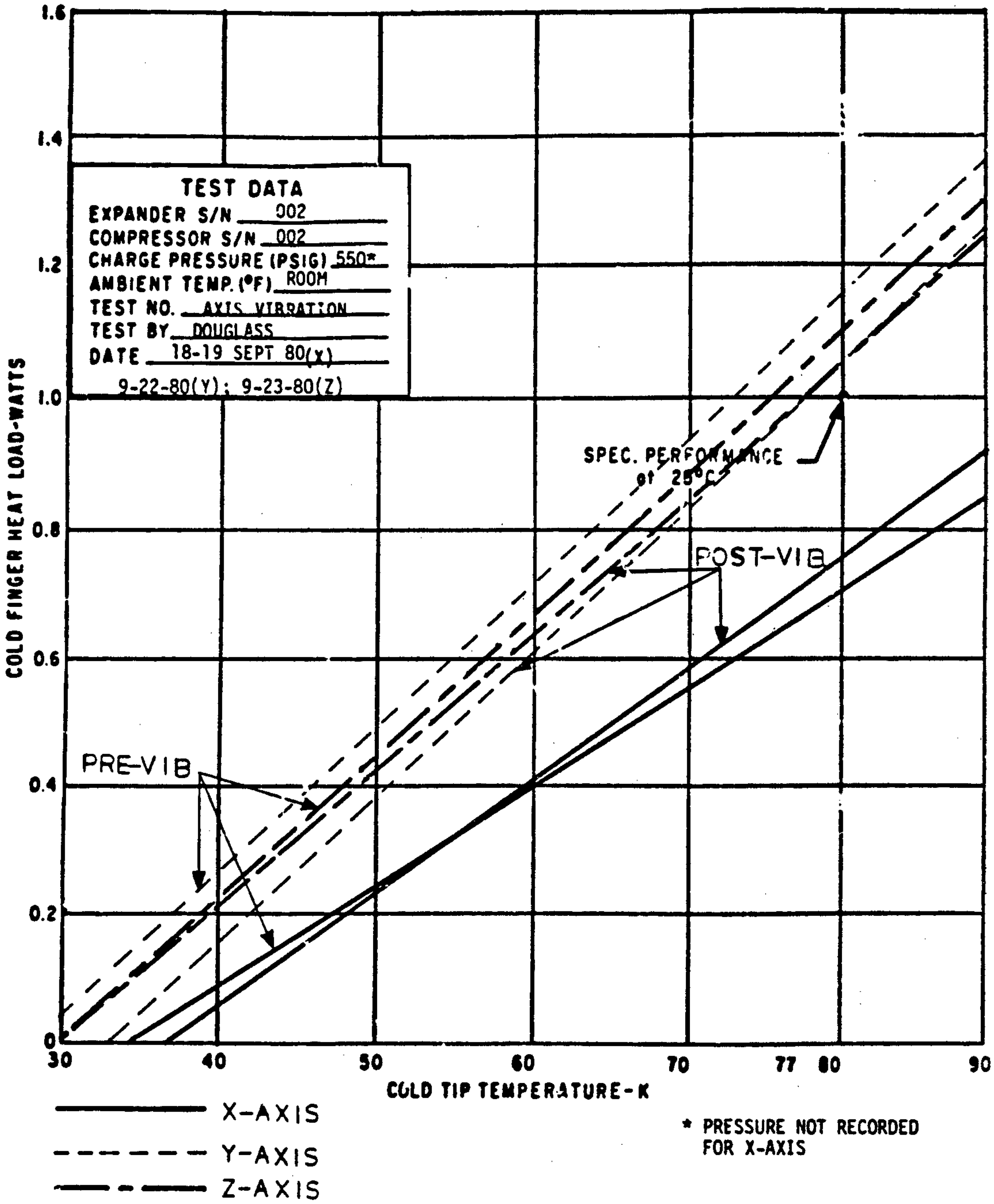


FIGURE 25. S/N 002 VIBRATION TEST - PERFORMANCE COMPARISON DATA FOR X, Y, AND Z AXES

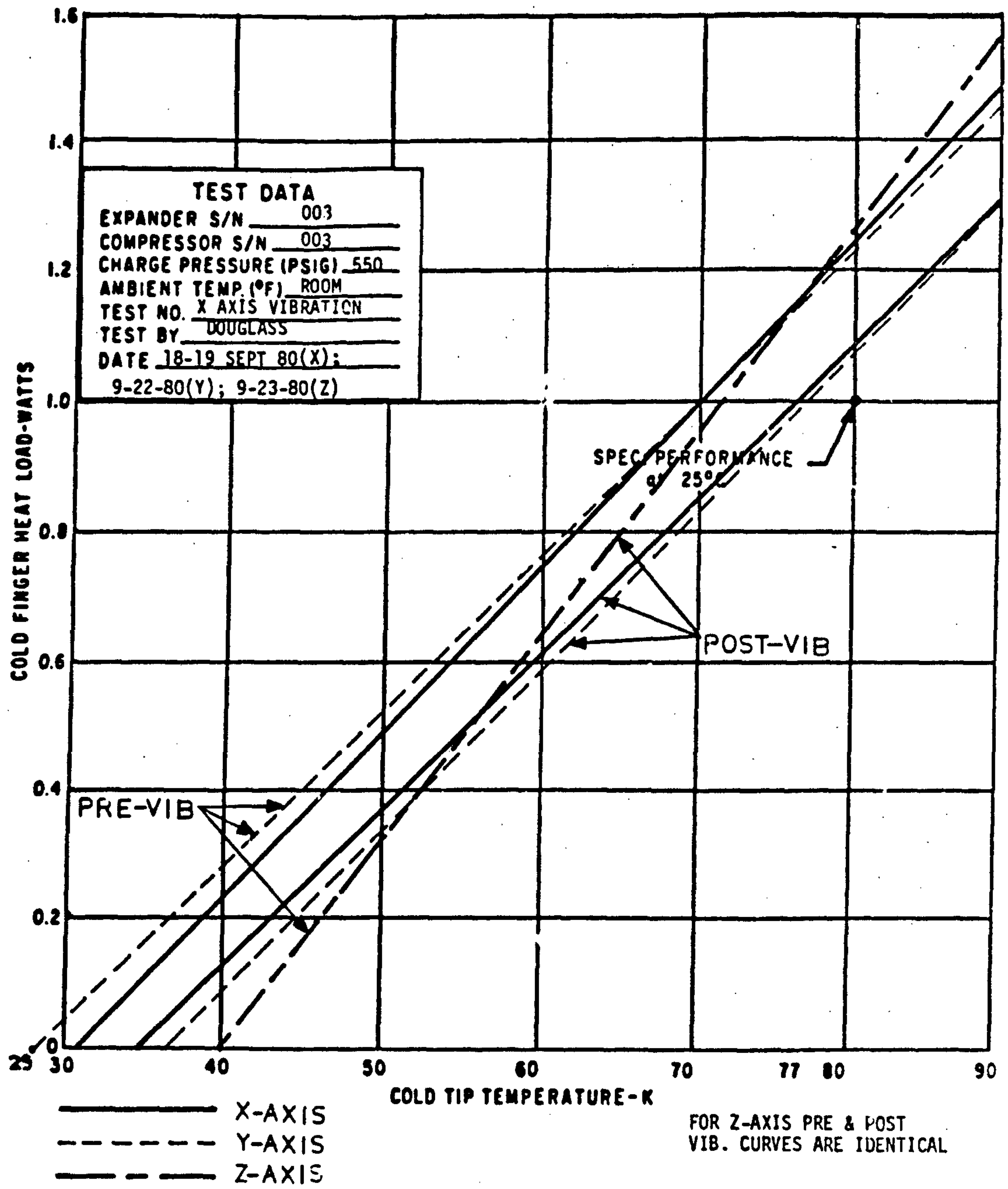


FIGURE 26. S/N 003 VIBRATION TEST -
PERFORMANCE COMPARISON DATA FOR X, Y, AND Z AXES

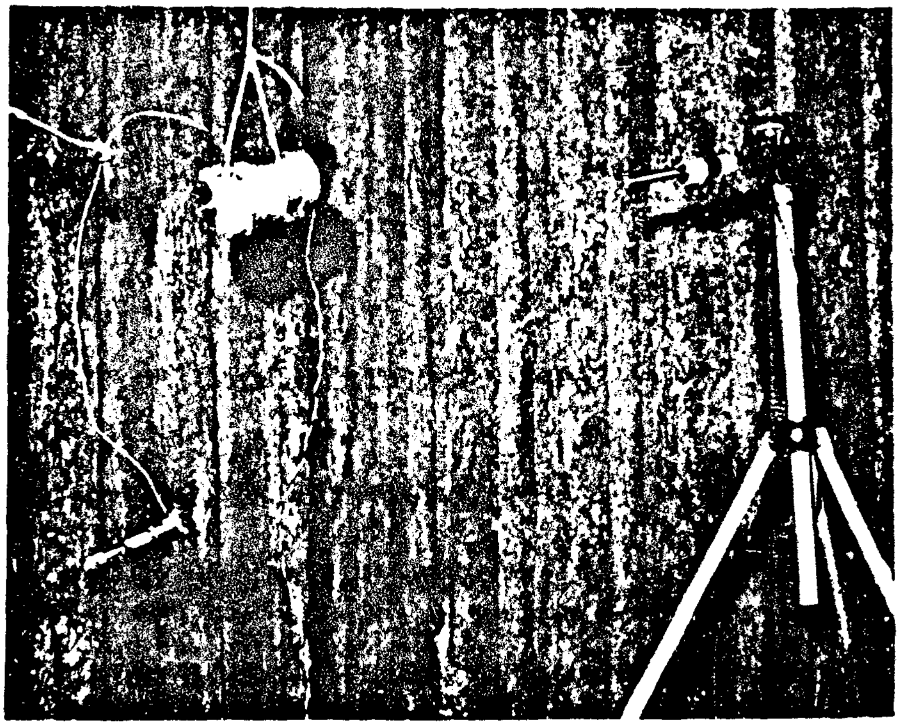


FIGURE 27. NOISE MEASUREMENT EQUIPMENT

where T is the peak torque, I is the moment of inertia about the principal axis, at a given frequency, was not to exceed 15.0 in-oz. semi-amplitude (design goal) for any of the first eight (8) harmonics of the motor axis and 3 in-oz. (semi-amplitude) for any of the first eight (8) harmonics of the other two axes.

The calculations for moments of inertia and the results of tests are included in the technical report of Bolt, Beranek and Newman, presented in Appendix III. Cryogenic coolers S/N 002, S/N 003, and S/N 001 (tested in a different time period) performed well with the exception of some deviations from the limits in the first three harmonics.

6.2.4 Acoustic Noise. Acoustic noise testing was subcontracted to Bolt, Beranek and Newman of Cambridge, MA under the direction of CTI-CRYOGENICS test personnel. Acoustic measurements were made on coolers S/N 001, S/N 002, and S/N 003 in an area where the background noise level was at least 10 db below the sound level to be measured. The coolers were operated and sound pressure measurements made with the coolers oriented to record the maximum level. Measurements were made with an octave-band analyzer with characteristics that complied with ANSI Specification 21.11-1971. The maximum sound pressure levels when measured at a distance of five (5) meters were not to exceed the noise values tabulated in Table II.

TABLE II. SOUND PRESSURE VALUES

Center Frequency - Hz	Octave Band - Hz	Maximum Sound Pressure Level (db)
125	87-175	49.5
250	175-360	48.5
500	350-700	43.5
1000	700-1400	35.5
2000	1400-2800	29.5
4000	2800-5600	29.5
8000	5600-11200	26.5

The Acoustical Measurements Procedure, calculations and results are presented in the technical reports from Bolt, Beranek and Newman as Appenidx IV. The cryogenic coolers passed the criteria for low noise when the cold finger was covered, as in operation. Cryogenic cooler S/N 002 exceeded the criteria for frequencies between 1500 to 2500 Hz and about 4100 Hz.

6.3 Life Test

The life test measurements required that three (3) cryogenic coolers be subjected to a 1000 hour Mean Time Between Failure (MTBF) in accordance with MIL-STD-781B, Plan IVA, per the life cycle pattern shown in Figure 28. In addition, 10 minutes of vibration was required for each cooler operating hour at a 2 g input and at a nonresonant frequency. Life testing has been divided into Phase I and Phase II for convenience of reporting. Phase I is the testing done at AVCO Environmental Test Facilities and Phase II is Life Testing conducted at CTI-CRYOGENICS.

6.3.1 Phase I - Testing with Vibration. AVCO Environmental Testing Services were put under contract for the Life Testing of the coolers since their vibration test equipment was adequate for the Life Test Program. Life Testing started with cyrogenic coolers S/N 001, S/N 005 and S/N 006, and progressed well until about 15 hours into the test program. S/N 001 failed because of problems with the hybrid control circuit and S/N 006 developed a gas leak. Life Testing was restarted, substituting S/N 004 for S/N 001 and again testing progressed well until about 100 hours into the test program. At this time S/N 004 and S/N 005 exhibited out-of-specification performance because of a small gas leak in S/N 004 and an unexplained abnormality in S/N 005 at -40°F. Testing continued on until approximately 356 hours of total life testing was accumulated when it was

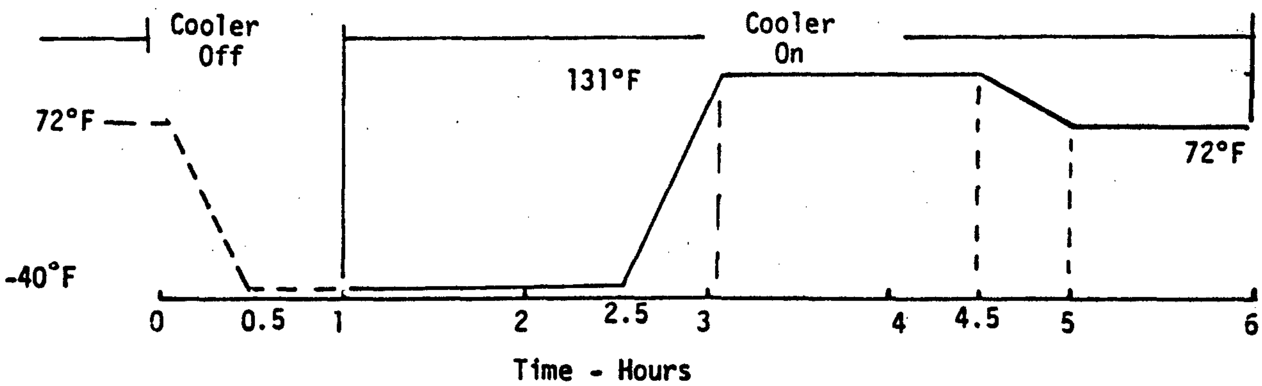


FIGURE 28. 1000 HOUR MTBF LIFE CYCLE PATTERN

noted that all three coolers were operating out of specification limits (refer to Table III). The life test was terminated and the coolers were disassembled to determine the cause of performance degradation. Disassembly of the cryogenic coolers showed the main cause for failure in all three units to be elongated holes in the aluminum pistons at the wrist pin engagement point. These failures occurred because the aluminum pistons were not hard coated.

It was decided, with NV & EOL's concurrance, that if the bearings, seals, bushings, rings, pins and pistons were replaced and the pistons hard anodized coated, the Life Tests could be repeated. NV & EOL also waived the 2 g vibration requirement that was superimposed on the life test cycle. Eliminating the vibration requirement allowed the continuation of testing to be conducted at CTI-CRYOGENICS' facility.

TABLE III. PHASE I LIFE TEST HOURS

COOLER S/N	OPERATING TIME
004	98 Hours
005	129 Hours
006	129 Hours
	356 Hours

6.3.2 Phase II - Testing without Vibration. The three cryogenic coolers, S/N 004, S/N 005, and S/N 006 were rebuilt with new hardware as required. Some difficulty was experienced with the cold end displacer seal configuration and minor design modifications were made to the seal and its spring before cooler performance was considered satisfactory to start life test. After preliminary performance testing was completed, life testing was started at CTI-CRYOGENICS with the three coolers mounted in a central vacuum dewar as shown in Figure 29. The overall test support equipment is shown in Figure 30.

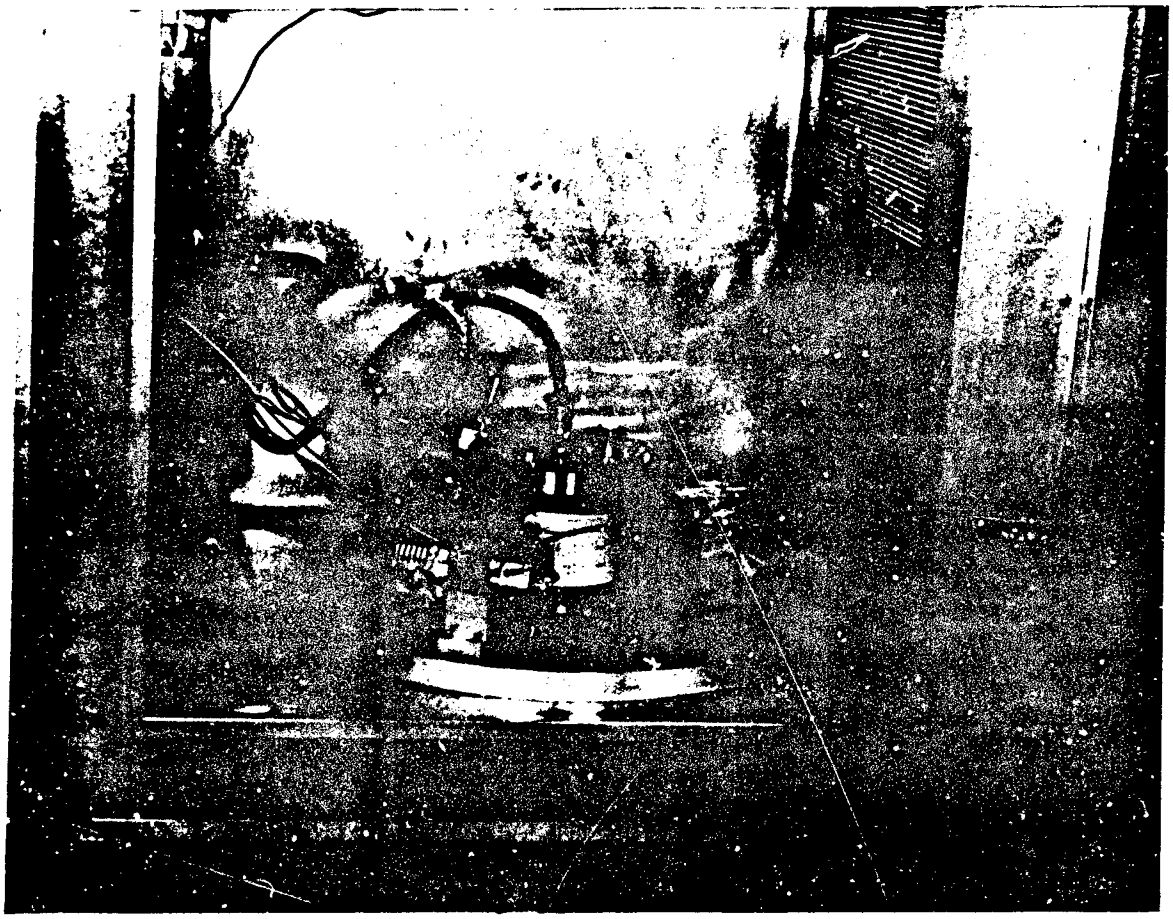


FIGURE 29. LIFE TEST FIXTURE WITH CENTRAL VACUUM DEWAR

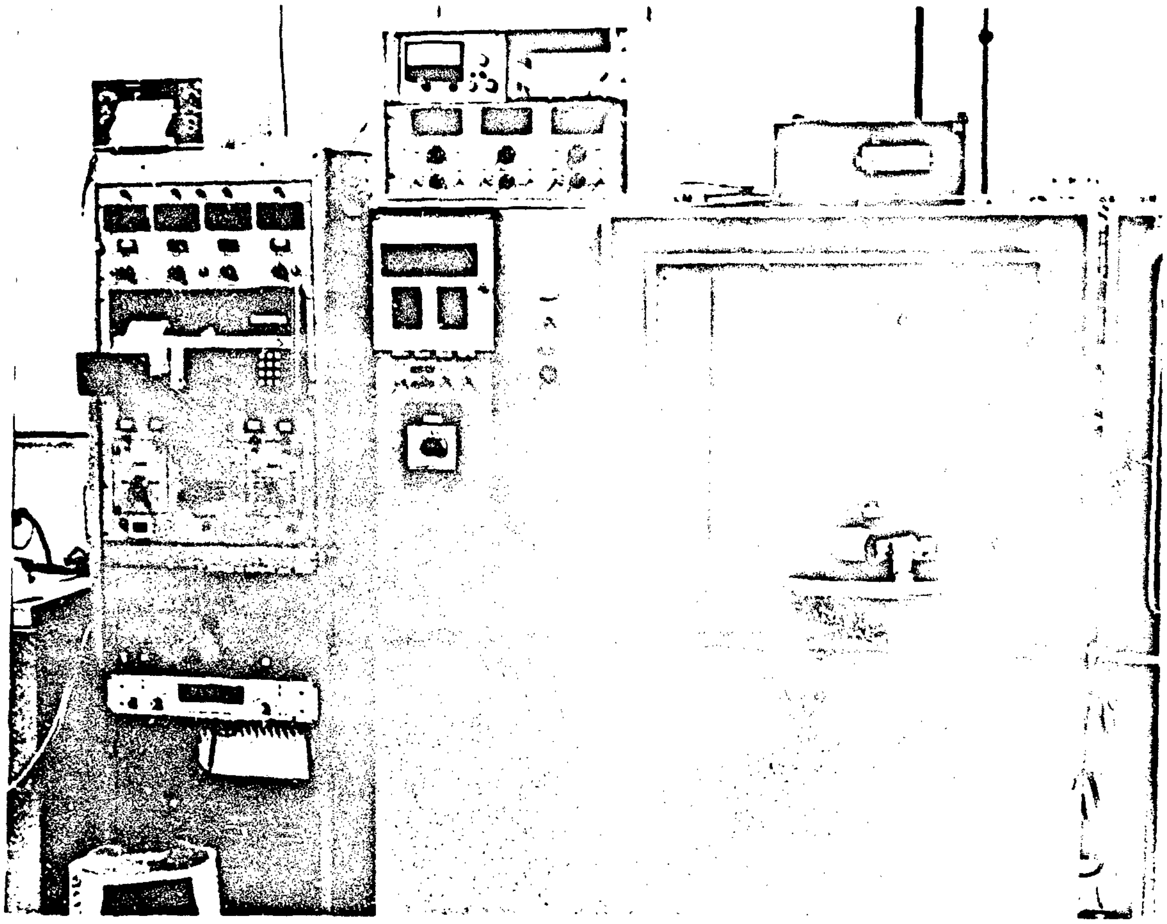


FIGURE 30. LIFE TEST CHAMBER AND SUPPORT INSTRUMENTATION

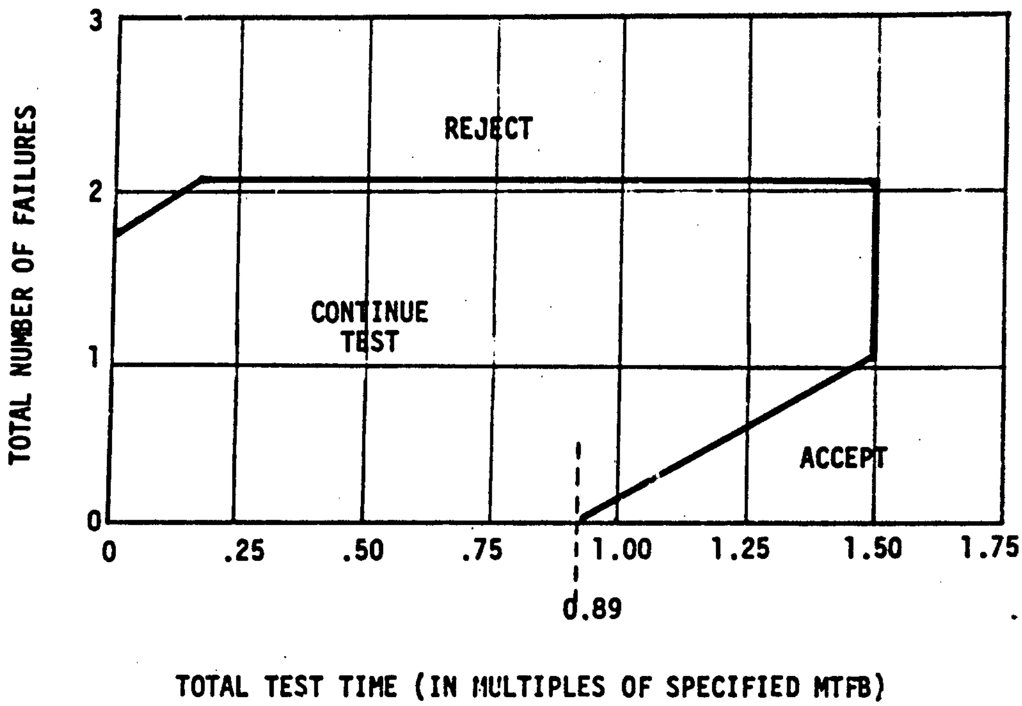
Testing progressed well for about 33 hours, when the temperature control in the environmental chamber malfunctioned and temperature raised above 180°F. All coolers continued to operate but some gas leakage occurred as the result of the high temperature. This condition occurred twice during testing. In each incident, seals were tightened, gas added to the coolers, and testing was continued since it was considered to be a non-relevant failure induced by test equipment malfunction.

Life testing continued; however, the difficulties experienced with temperature control on CTI-CRYOGENICS' thermal chamber indicated a need for caution. With concurrance from NV & EOL, CTI-CRYOGENICS continued life testing in a "Manual Mode" as opposed to an automatic programmed mode. This meant that during nights and week-end hours, the thermal test chamber was operated at a single specific temperature rather than the programmed cycle of Figure 28.

Based on the MTBF curve of MIL-STD-781B, for Plan IVA (Figure 31), the total test time on all three cryogenic coolers can equal 890 hours, with no failures, and be acceptable for a 1000 MTBF qualification, provided no single equipment "ON" time is less than one half the average operating time of all equipments on test. With these conditions in mind, CTI-CRYOGENICS officially concluded the life test program at the following times as shown in Table IV.

TABLE IV. PHASE II LIFE TEST HOURS

Cooler S/N	Operating Time
004	230 Hours
005	330 Hours
006	330 Hours
	890 Hours



TOTAL TEST TIME

No. of Failures	Reject (Equal or Less)	Accept (Equal or More)
0	N/A	0.89
1	N/A	1.44
2	.12	1.50
3	1.50	N/A

FIGURE 31. ACCEPT-REJECT CRITERIA - PLAN IVA

Prior to completion of the life test program, CTI-CRYOGENICS received a waiver from NV & EOL to allow a 20% reduction in thermal loads after 200 hours of Life Test operation. However, during the actual life test program, the waiver was found to be unnecessary and therefore was not implemented. All three cryogenic coolers exceeded the performance requirements at all temperatures. Figures 32, 33, and 34 show typical performance curves for the coolers during the life testing.

Subsequent to the conclusion of the life test program, CTI-CRYOGENICS elected to operate the coolers longer to acquire more testing hours on the coolers.

A summary of the cryogenic cooler life test hours at various temperatures, compared to the target hours per the cycle pattern of Figure 28, is shown in Table V.

Table VI shows the total life test hours per cooler plus the additional hours of testing in excess of the 890 hour minimum requirement. In total, the three cryogenic coolers received 1184 hours of operational testing before failures occurred.

TABLE V. CM-4 LIFE TEST CYCLE SUMMARY HOURS BY TEMPERATURE FOR S/N 004, S/N 005, AND S/N 006

Cooler S/N	-40°F	+72°F	+131°F	Temperature Transition
004	48.5	118.5	30.5	19.0
005	78.5	149.0	58.0	37.5
006	110.0	169.0	89.5	58.0
TOTALS (HOURS):	237.0	436.5	178.0	114.5

GRAND TOTAL: 966 Hours + 42 Hours* = 1008** Hours

Additional hours on coolers during baseline testing = + 167 Hours

1184 Operational Hours

*Operating hours in spec but no chamber temperature data.

**1008 HOURS NO FAILURES PER TEST PLAN IVA OF MIL-STD-781B.

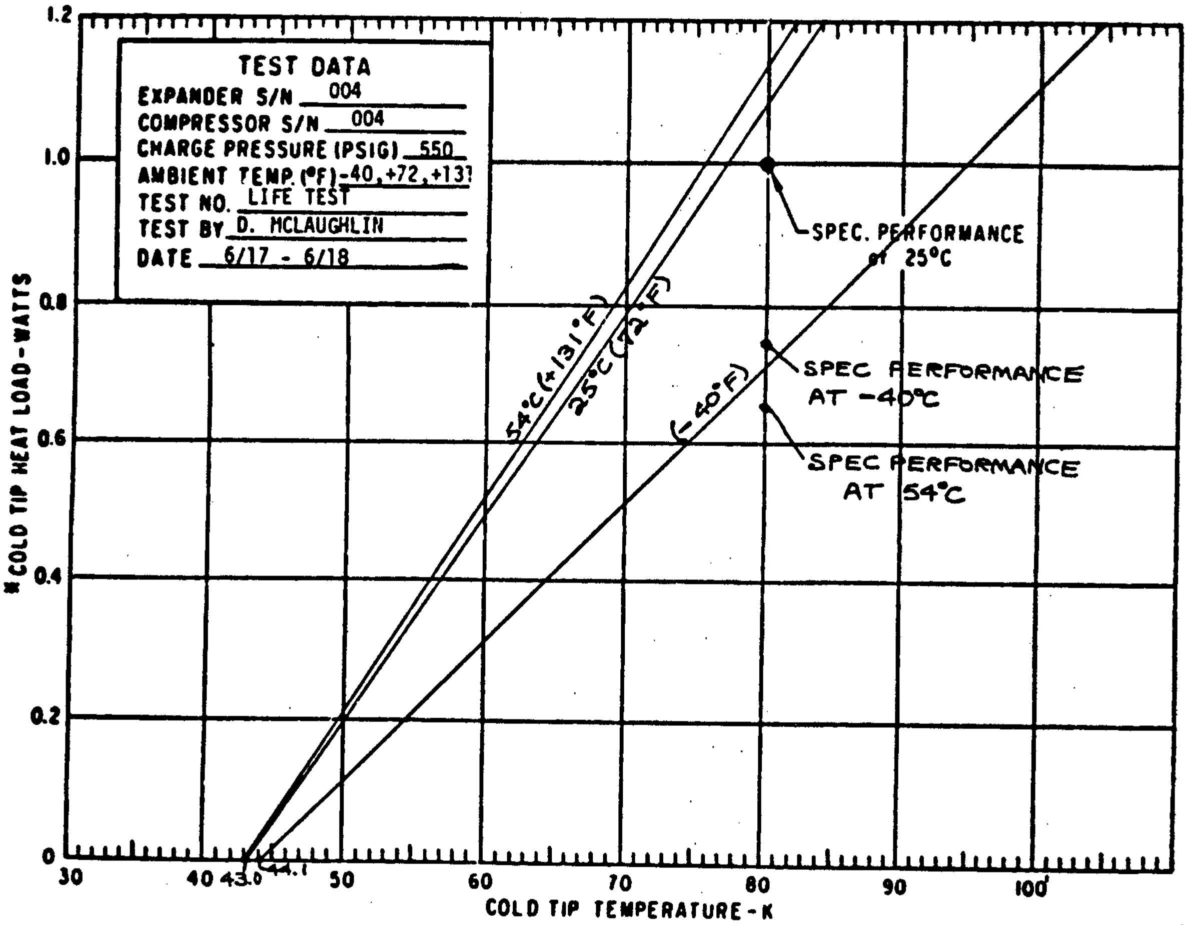


FIGURE 32. S/N 004 PERFORMANCE CURVES

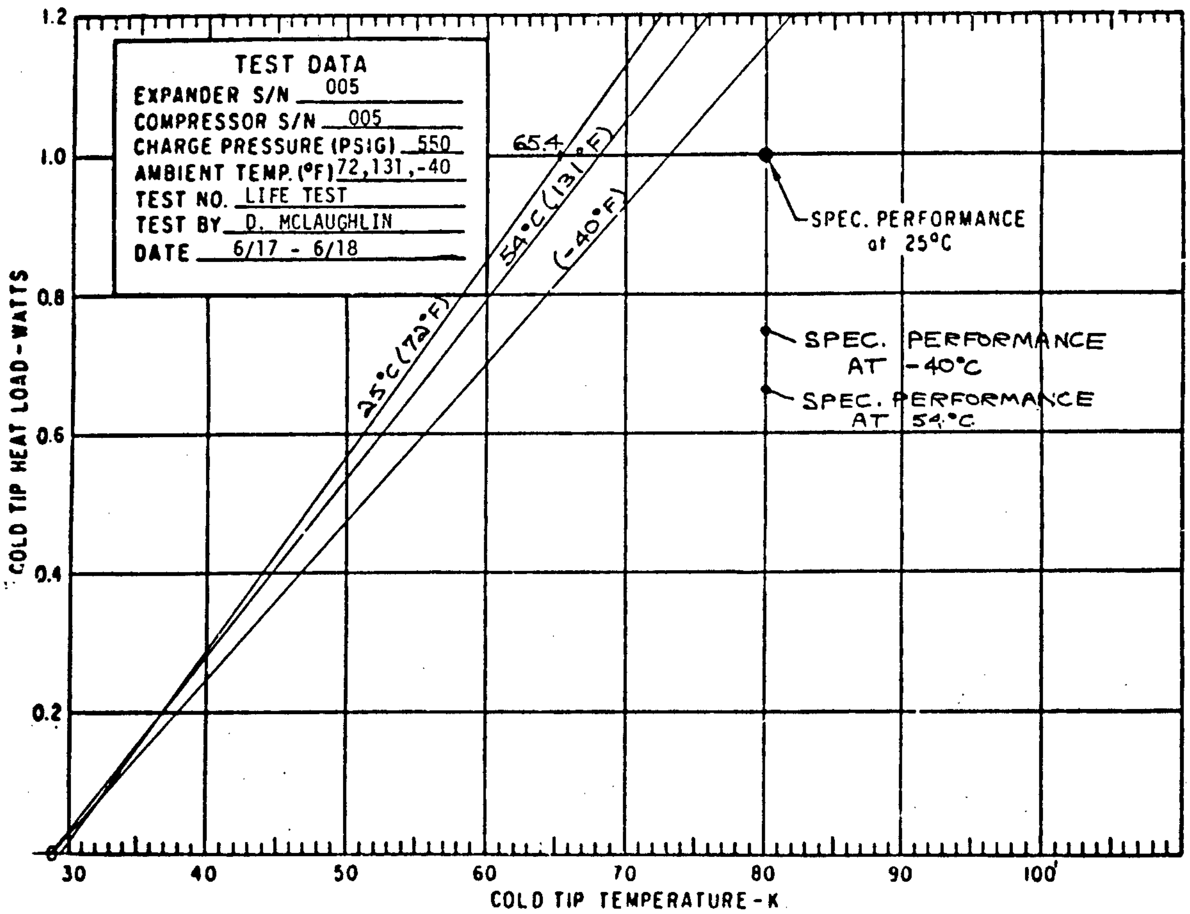


FIGURE 33. S/N 005 PERFORMANCE CURVES

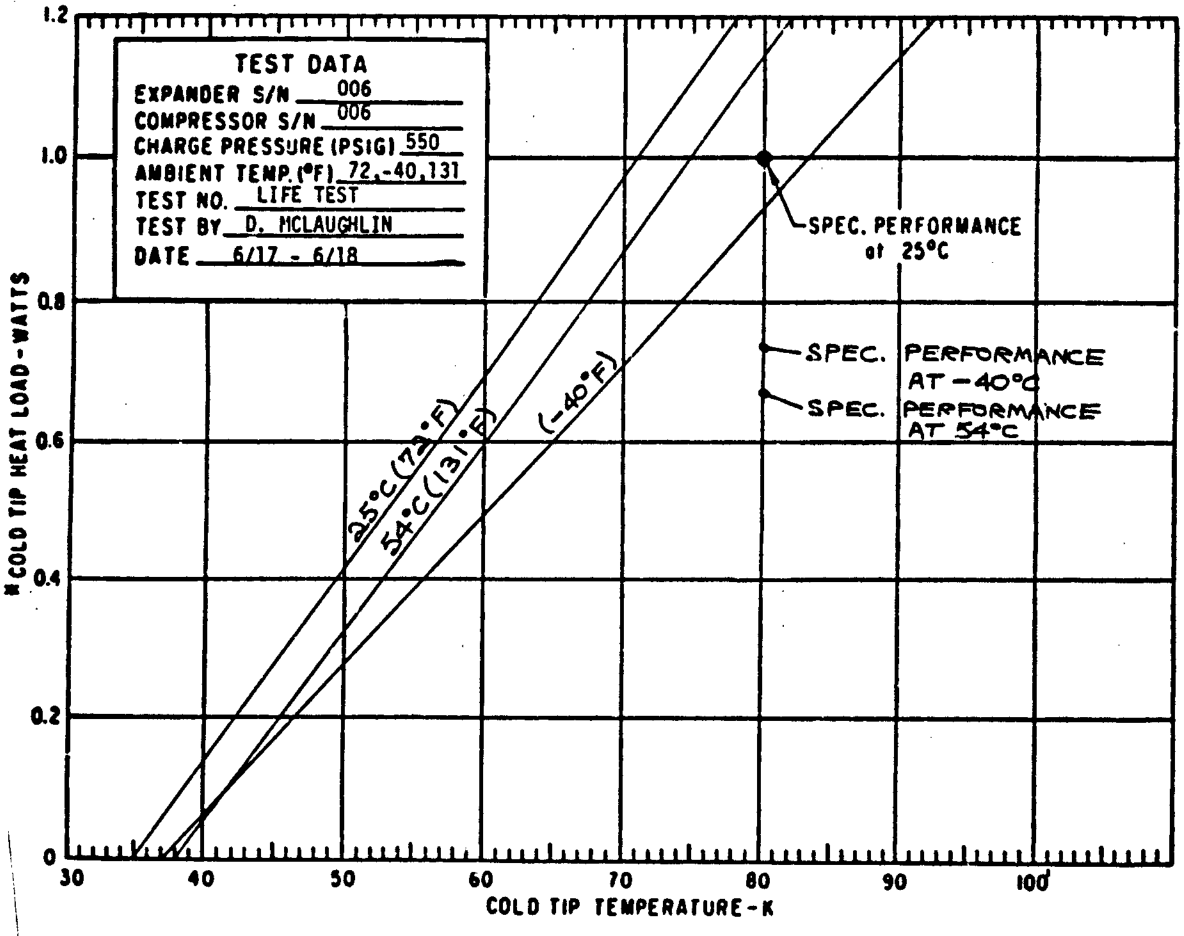


FIGURE 34. S/N 006 PERFORMANCE CURVES

TABLE VI. CM-4 LIFE TEST CYCLE SUMMARY HOURS
COMPARISON FOR S/N 004, S/N 005, AND S/N 006

	004		005		006	
Operating Condition	Hrs. Actual	Hrs. Target	Hrs. Actual	Hrs. Target	Hrs. Actual	Hrs. Target
-40°F (operating loaded & unloaded)	48.5	69.	77.0	99.	77.0	99.
-40/131°F (operating loaded)	10.5	23.	19.0	33.	19.0	33.
+131°F (operating loaded & unloaded)	*30.5	69.	*55.5	99.	*55.5	99.
+131/72°F (operating - no load)	8.5	23.	17.0	33.	17.0	33.
72°F (operating - loaded)	118.5	46.	147.0	66.	147.0	66.
	216.5	230.	315.5	330.	315.5	330.
Hours of operation in spec --------- (no chamber temperature data)	13.5	___	14.5	___	14.5	___
TOTAL HOURS ------------------------	230.0	230.	330.0	330.	330.0	330.

890 HOURS NO FAILURES PER TEST PLAN IVA OF MIL-STD-781B

*6/12/82 @ 33 hours into test experienced 181°F chamber temperature for four operational hours. 6/18/82 @ 104 hours into test experienced 200°F+ chamber temperature for 14 operational hours.

Cryogenic coolers S/N 004 and S/N 005 experienced failures after the completion of life tests. These failures were the result of an accidental high temperature rise in the test chamber during the life tests. The high temperatures caused bearing lubrication breakdown, leading to premature bearing wear and failure.

Cooler S/N 006 also experienced post life test failure because of the accidental high temperature. In this case, the excessive heat caused the hybrid circuit board assembly to separate from its attachment point on the heat sink above the motor stator. Without the benefit of the heat sink, the hybrid overheated and eventually opened circuits, causing the motor to shut down.

7.0 CONCLUSIONS

The testing and results presented in this report support the position that the Split-Stirling 1.0 Watt Cryogenic Cooler meets the environmental and physical requirements necessary for the intended military use as noted below in Table VII.

TABLE VII. PERFORMANCE SUMMARY

Requirement	Condition
° Cooldown time to 80K	Satisfactory
° Weight under 4 pounds	Satisfactory
° Operating performance temperature limits of -40°C to +55°C	Satisfactory
° Temperature-Shock and High-Low Temperature operating	Satisfactory
° Mechanical Shock	Satisfactory
° Sinusoidal Vibration	Satisfactory
° Self-Induced Vibration	Satisfactory except for 3 harmonics
° Acoustics	Satisfactory except for high and low frequency deviations on 1 cooler
° 1000 Hour MTBF	Satisfactory
° Locked rotor torque and staring torque time	Satisfactory
° Physical profile	Satisfactory

8.0 POST PROGRAM TEST RESULTS

At the completion of the testing required on all six cryogenic coolers, each cooler was disassembled and refurbished with new parts as required because of wear or deterioration.

Each of the six rebuilt cryogenic coolers, S/N 001, S/N 002, S/N 003, S/N 004, S/N 005, and S/N 006, were then subjected to a final performance test at the required high, low, and ambient temperatures per the requirements of Appendix V. The performance data for each cooler is shown in Figures 35 through 40.

These coolers will be shipped to NV & EOL.

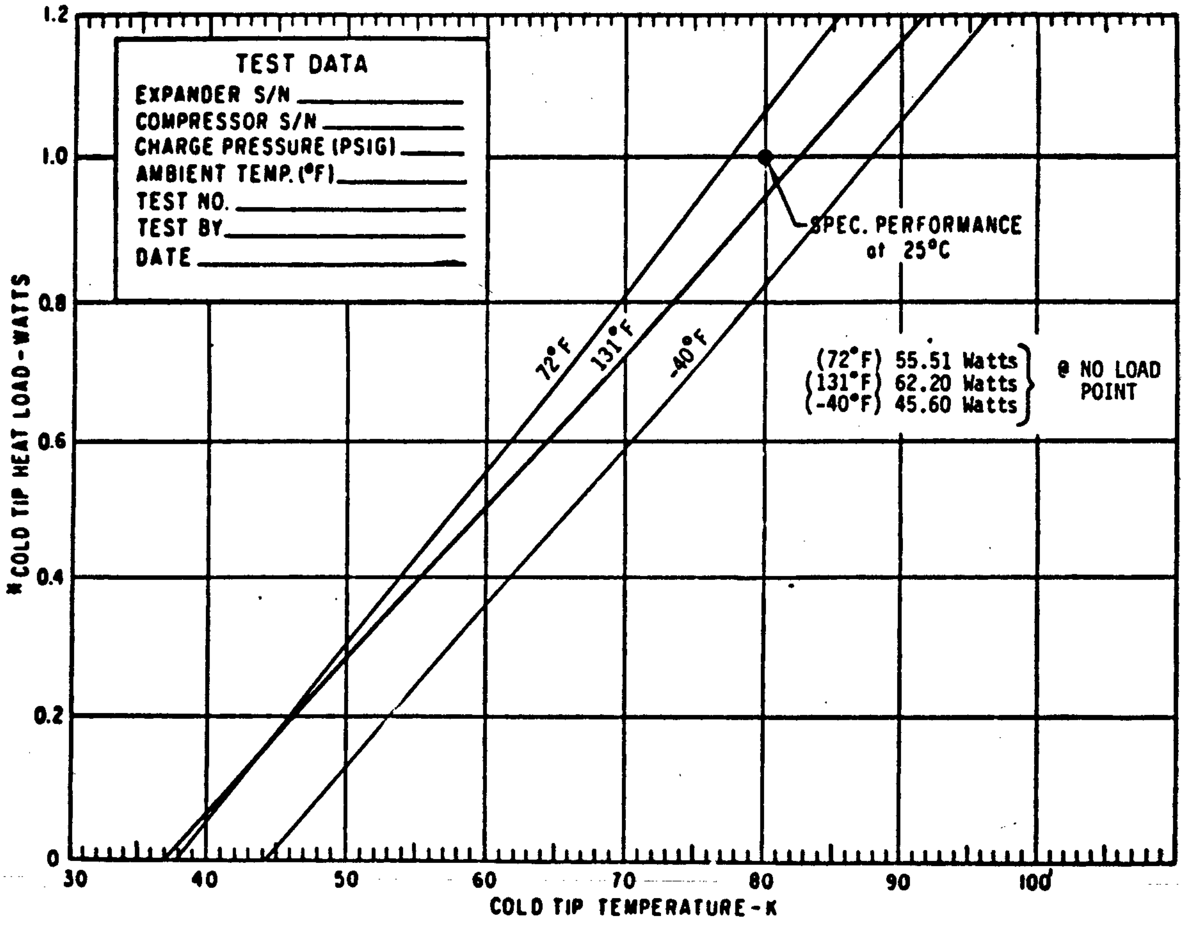


FIGURE 35. POST PROGRAM PERFORMANCE DATA, S/N 001

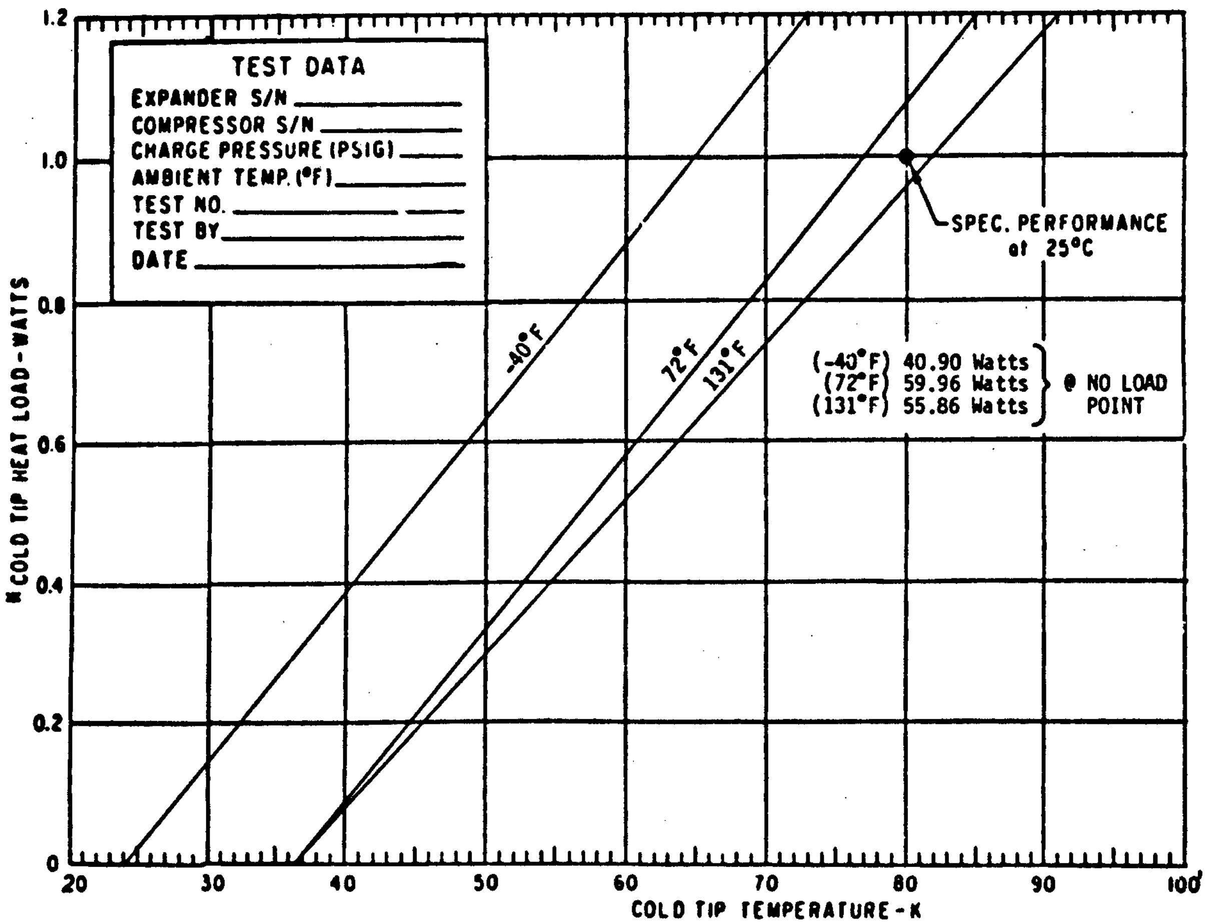


FIGURE 36. POST PROGRAM PERFORMANCE DATA, S/N 002

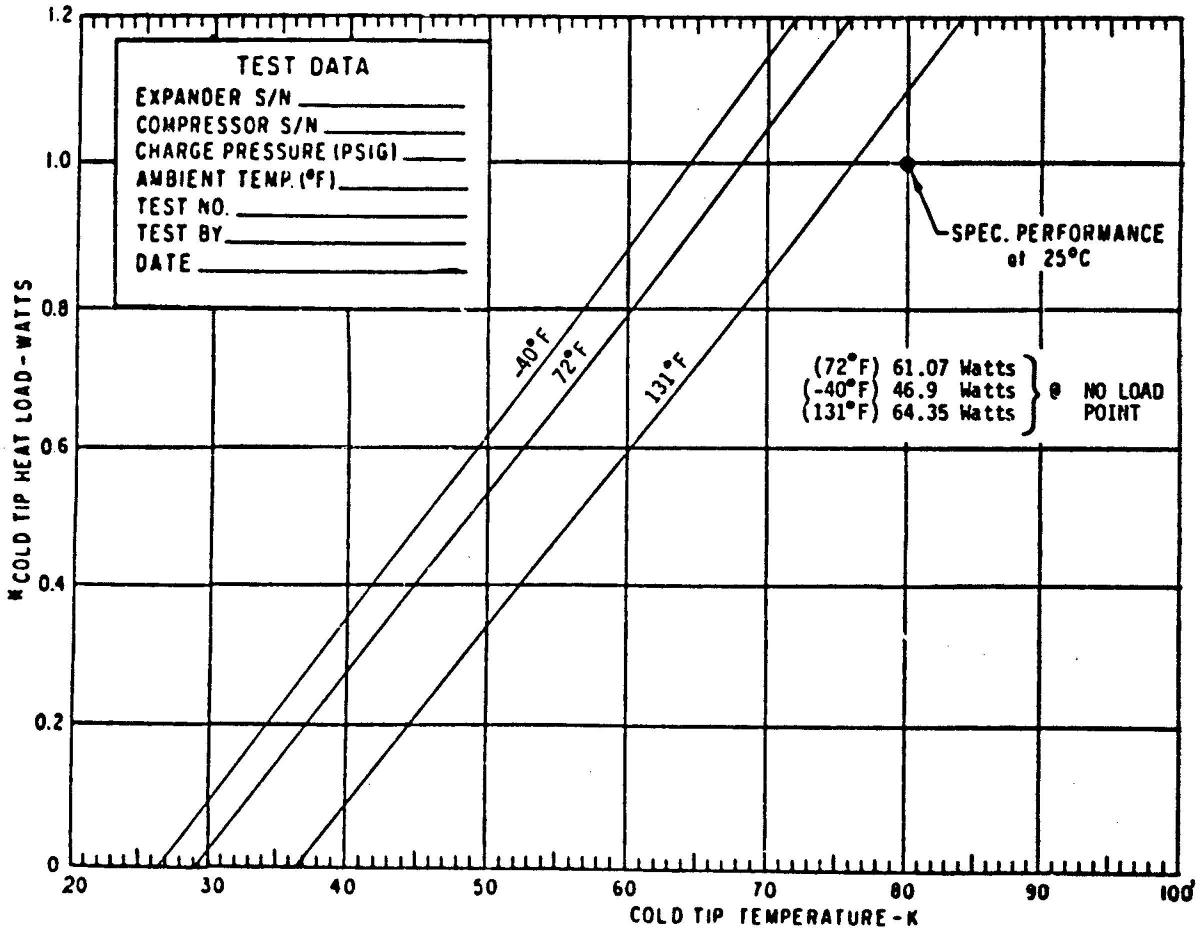


FIGURE 37. POST PROGRAM PERFORMANCE DATA, S/N 003

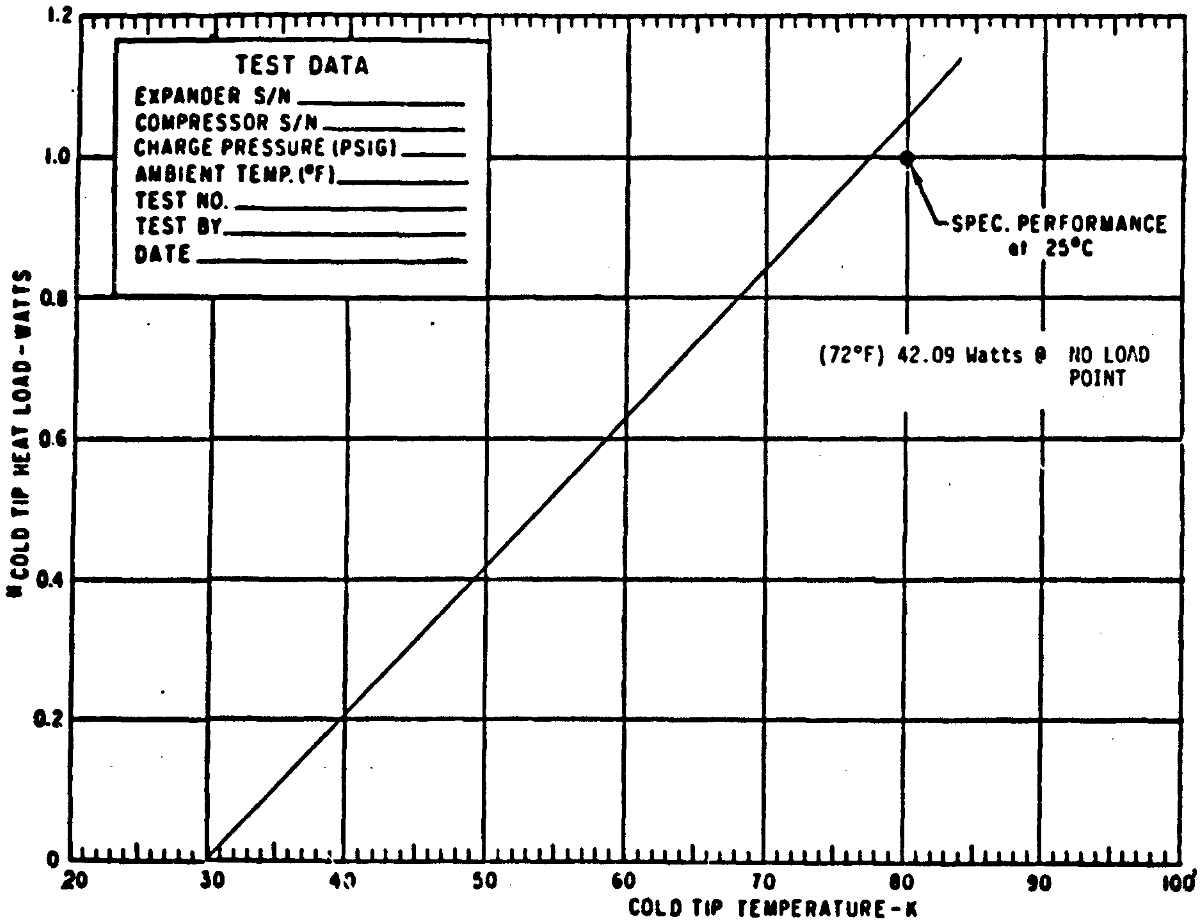


FIGURE 38. POST PROGRAM PERFORMANCE DATA, S/N 004

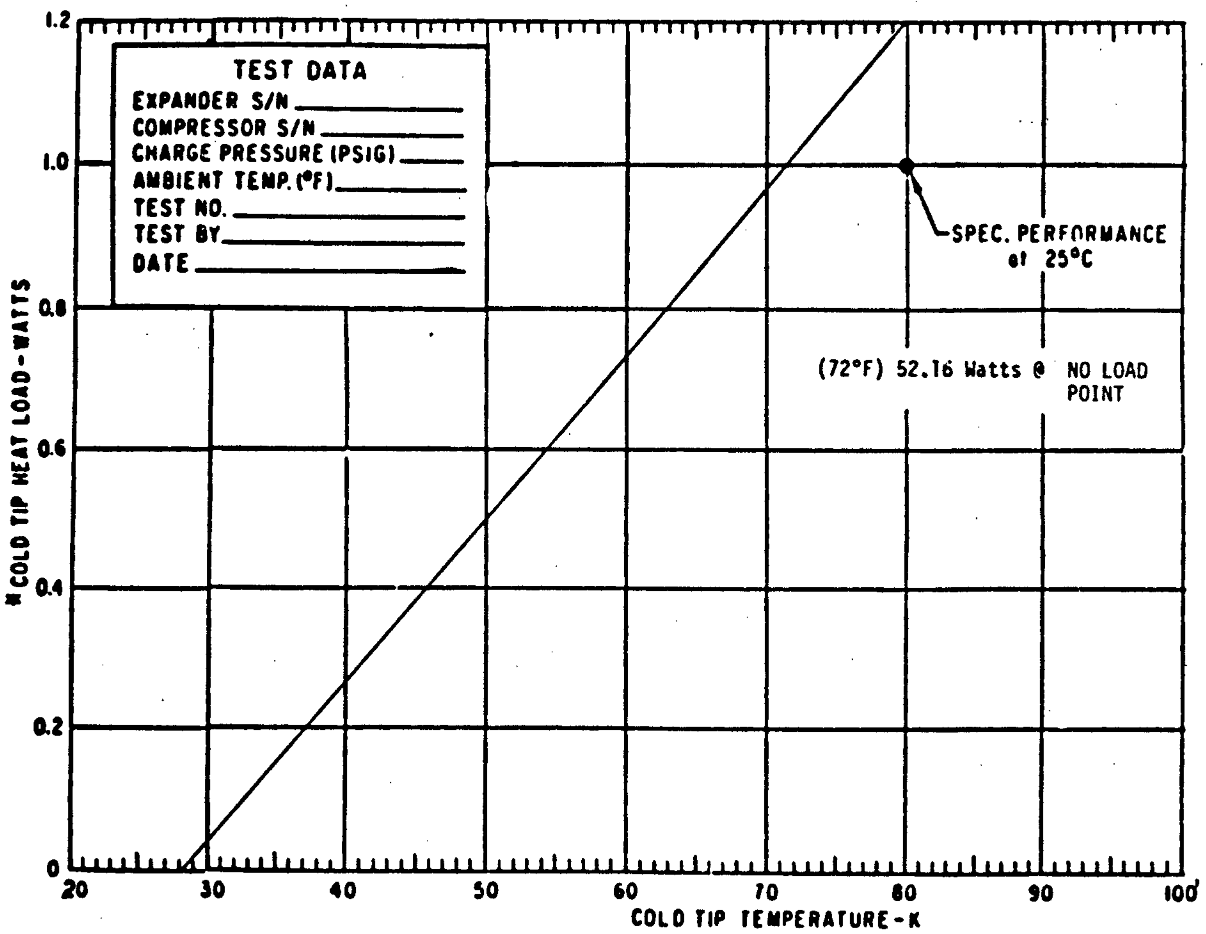


FIGURE 39. POST PROGRAM PERFORMANCE DATA, S/N 005

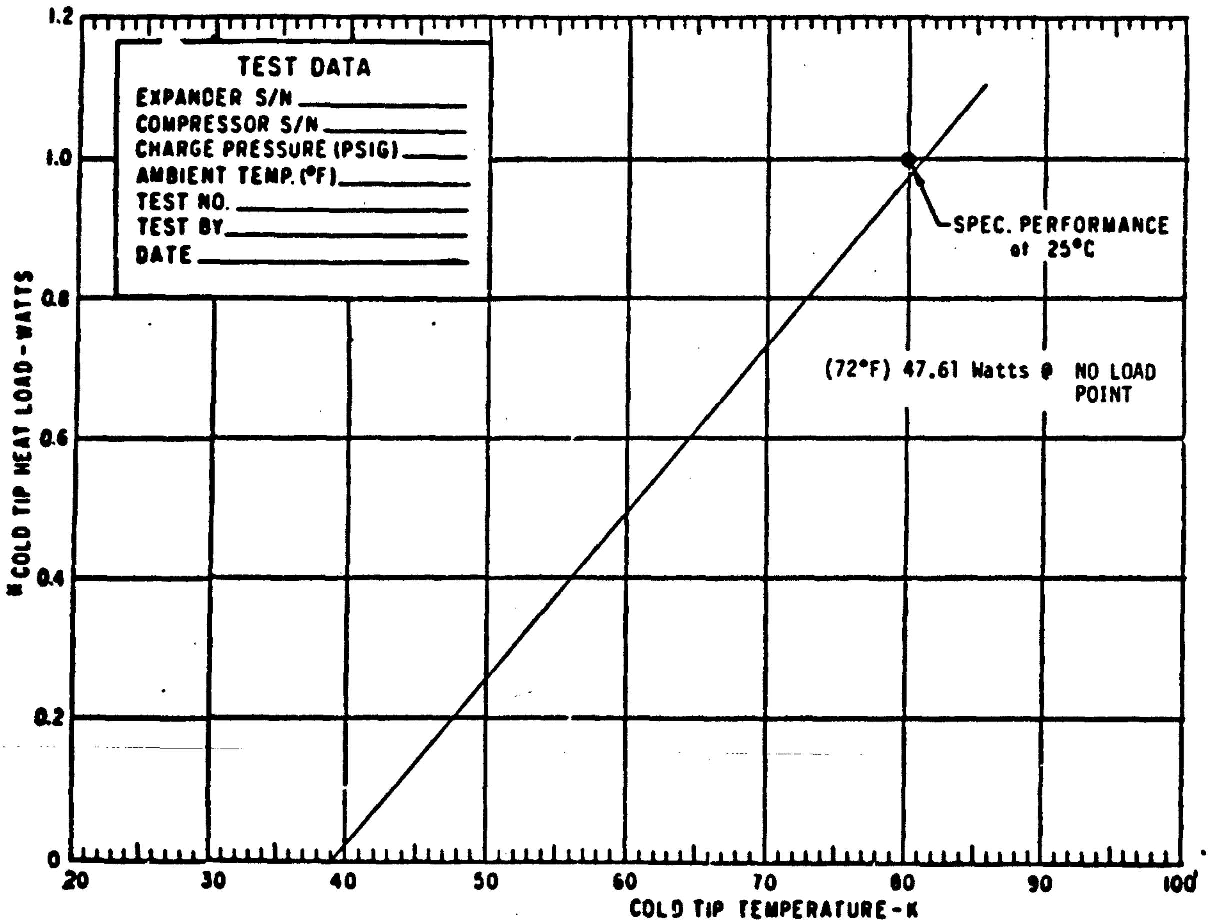


FIGURE 40. POST PROGRAM PERFORMANCE DATA, S/N 006

APPENDIX I

MECHANICAL SHOCK

Test Certification

201 LOWELL STREET, WILMINGTON, MASS 01887

TEST CERTIFICATE

CUSTOMER	P.O. NO.	WORK ORDER NO.
CTI Cryogenics	747412	1673
ADDRESS: 266 Second Avenue, Waltham MA 02154		DATE: 22 December 1980
TEST ITEM: NV/EOL 1.0 Watt Miniature Cooler	MODEL/SERIAL NO. D807600-1, S/N 002 D807600-2, S/N 003	
TEST TITLE: Shock	APP. SPEC.: MIL-STD-810B	TEST DATE(S): 3 September 1980

TEST PROCEDURE

SHOCK

The Cooler Assembly was firmly mounted to the test fixture and shock tested in accordance with Test Procedure IV established in MIL-STD-810B, conducted separately in each direction of the three principal axes.

Impact Shock - The NV/EOL Cooler Assembly, at ambient room temperature and operating, was firmly torqued to the SM110 shock machine and subjected to impact shock tests consisting of a sawtooth pulse profile at 100g and 11 milliseconds, applied two times in each direction of the three principal axes (12 shocks). To verify the limits of the test control signal, the output of the control accelerometer was recorded on Polaroid photo with a scope camera.

INSTRUMENTATION	MFGR.	MODEL NO	SERIAL NO.	CAL. DATE
Shock Machine	Avco	SM110	1017	Prior to use
Accelerometer	Endevco	2213C	GR28	3/80-3/81
Cathode Follower	Calidyne	4000R	R7493	10/80-10/81
Bandpass Filter	Krohn-Hite	335	52049	4/80-4/82
Oscilloscope	Tektronix	535A	34675	12/79-12/80
Calibrator	Ballantine	420	1302	6/80-6/81

TEST ENGINEER	DATE	CHIEF ENVIRONMENTAL SERVICES	DATE
[signature]	12/22/80	[signature]	12-22-80
TEST WITNESS	DATE	GOVERNMENT INSPECTOR	DATE

APPENDIX II

VIBRATION

Resonance search, resonant dwell, and
cycling dwell for Airborne and Ground

TEST CERTIFICATIONS

201 LOWELL STREET, WILMINGTON, MASS 01887

TEST CERTIFICATE

CUSTOMER	P.O. NO.	WORK ORDER NO.
CTI Cryogenics	747412	1673
ADDRESS 266 Second Avenue, Waltham MA 02154		DATE 22 December 1980
TEST ITEM NV/EOL - 1.0 Watt Miniature Cooler	MODEL/SERIAL NO.	D8076001 - S/N 002 D8076002 - S/N 003
TEST TITLE Sine Vibration	APP. SPEC. MIL-STD-810B	TEST DATE(S) 18-23 September 1980

TEST PROCEDURE

VIBRATION:

This certificate defines the test levels and procedures used to qualify one miniature Cooler Assembly. The Cooler Assembly, instrumented with 5 accelerometers, was connected to the test setup and vibrated in accordance with the test conditions established in Method 514.1 of Test Procedure VIII of the MIL-STD. To verify the limits of the test control signal and to provide safe shutdown, the output of the control accelerometer was analyzed during the test and used to actuate the safety interlock at 140 percent of level.

SINUSOIDAL VIBRATION

Resonant Search - Each Cooler Assembly, operating, was subjected to simple harmonic motion at frequencies from 5 to 500 cps at vibration amplitudes equal to those shown in Table I. The change in frequency was varied logarithmically, traversing 5 to 500 cps in 7.5 minutes, applied one time to determine resonances in each of the three principal axes.

INSTRUMENTATION	MFGR.	MODEL NO.	SERIAL NO.	CAL. DATE
Vibration System #1				
Shaker	MB	C25HB	AF290	12/79-12/80
Sine Control	UD	M100	AF3518	12/79-12/80
Accelerometer	Endevco	2213C	AF3518	12/79-12/80

TEST ENGINEER	DATE	CHIEF ENVIRONMENTAL SERVICES	DATE
[signature]	12/22/80	A. A. Kochilas	12/22/80
TEST WITNESS	DATE	GOVERNMENT INSPECTOR	DATE

TABLE I

Frequency (cps)	Amplitude	Duration
5-20	0.50" D.A.	7.5 Minutes
20-500	1.0g	

Resonant Dwell - The Miniature Cooler Assembly, while operating, was subjected to resonant dwell tests at the frequency observed during the resonant search. The dwell frequencies and input levels used for the dwell tests conducted during the airborne vibration tests are shown in Table II.

TABLE II

Axis	Frequency (cps)	Amplitude	Time
X-X	160	5.0g	30 Minutes
	500	5.0g	30 "
Y-Y	25	5.0g	30 "
	275	5.0g	30 "
Z-Z	22	4.0g	30 "
	140	5.0g	30 "

Cycling Dwell - The Miniature Cooler Assembly, operating, was subjected to sinusoidal cycling dwells at frequencies from 5 to 500 cps at the vibration amplitudes shown in Table III and defined in Figure 514.1-6 and Curve W of the test procedure. The change in frequency was varied logarithmically from 5 to 500 to 5 cps, traversing a complete cycle in 15 minutes. The cycle was repeated 8 times in each of the three principal axes for a total time of 2.0 hours each axis.

TABLE III

Axis	Frequency (cps)	Amplitude	Duration
X,Y,Z	5-11.5	0.65" D.A.	7.5 Min.
	11.5-500	4g	

201 LOWELL STREET, WILMINGTON, MASS 01887

TEST CERTIFICATE

CUSTOMER	P.O. NO.	WORK ORDER NO.
CTI Cryogenics	747412	1673
ADDRESS		DATE
266 Second Avenue, Waltham MA 02154		22 December 1980
TEST ITEM	MODEL/SERIAL NO.	
NV/EOL - 1.0 Watt Miniature Cooler	D8076001 - S/N 002 D8076002 - S/N 003	
TEST TITLE	APP. SPEC.	TEST DATE(S)
Sine Vibration	MIL-STD-810B	18-23 September 1980

TEST PROCEDURE

VIBRATION:

This certificate defines the test levels and procedures used to qualify one miniature Cooler Assembly. The Cooler Assembly, instrumented with 5 accelerometers, was connected to the test setup and vibrated in accordance with the test conditions established in Method 514.1 of Test Procedure I of the MIL-STD. To verify the limits of the test control signal and to provide safe shutdown, the output of the control accelerometer was analyzed during the test and used to actuate the safety interlock at 140 percent of level.

SINUSOIDAL VIBRATION

Resonant Search - Each Cooler Assembly, operating, was subjected to simple harmonic motion at frequencies from 5 to 2000 cps at vibration amplitudes equal to those shown in Table I. The change in frequency was varied logarithmically, traversing 5 tc 2000 cps in 20 minutes, applied one time to determine resonances in each of the three principal axes.

INSTRUMENTATION	MFGR.	MODEL NO.	SERIAL NO.	CAL. DATE
Vibration System #1				
Shaker	MB	C25HB	AF290	12/79-12/80
Sine Control	UD	M100	AF3518	12/79-12/80
Accelerometer	Endevco	2213C	AF3518	12/79-12/80

TEST ENGINEER	DATE	CHIEF ENVIRONMENTAL SERVICES	DATE
[signature]	12/22/80	[signature]	12-22-80
TEST WITNESS	DATE	GOVERNMENT INSPECTOR	DATE

TABLE I

Frequency (cps)	Amplitude	Duration
5-20	0.50" D.A.	10 Minutes
20-2000	1.0g	

Resonant Dwell - The Miniature Cooler Assembly, while operating, was subjected to resonant dwell tests at the frequency observed during the resonant search. The dwell frequencies and impact levels used for the dwell tests are shown in Table II.

TABLE II

Axis	Frequency (cps)	Amplitude	Time
X-X	160	5.0g	30 Minutes
	500	5.0g	30 "
	777	5.0g	30 "
	1690	5.0g	30 "
Y-Y	25	5.0g	30 "
	275	5.0g	30 "
	621	5.0g	30 "
	928	5.0g	30 "
Z-Z	22	4.0g	30 "
	140	5.0g	30 "
	849	5.0g	30 "
	1900	5.0g	30 "

Cycling Dwell - The Miniature Cooler Assembly, operating, was subjected to sinusoidal cycling dwells at frequencies from 5 to 2000 cps at the vibration amplitudes shown in Table III and defined in Figure 514.1-1 and Curve M of the test procedure. The change in frequency was varied logarithmically from 5 to 2000 to 5 cps, traversing a complete cycle in 20 minutes. The cycle was repeated 3 times in each of the three principal axes for a total time of 1.0 hour each axis.

TABLE III

Axis	Frequency (cps)	Amplitude	Duration
	5-20	0.10" D.A.	
X,Y,Z	20-33	2.0g	10 Min.
	33-52	0.036" D.A.	
	52-2000	5.0g	

APPENDIX III

SELF-INDUCED VIBRATION

This appendix contains Calculations and Results extracted from Bolt Beranek and Newman's Technical Report dated 22 August 1980, verbatim.

50 Moulton Street
Cambridge, MA 02238
Telephone (617) 491-1850
Telex No. 92-1470

Bolt Beranek and Newman Inc.

22 August 1980

CTI Cryogenics
Kelvin Park
266 Second Avenue
Waltham, MA 02254

Attention: Mr. Fernando Faria

Subject: Vibration Measurements of CTI Cooler
BBN Project No. 154671

Dear Sir:

In July 1980, Bolt Beranek and Newman Inc. (BBN) performed a series of acoustic and vibration measurements on two CTI Crygenics Model CM-4 cooler units. This letter report discusses the measurement procedures and calculations, and presents the results of these tests.

MEASUREMENT PROCEDURE

The main cooler unit was suspended from the ceiling of BBN's anechoic chamber by a soft rubber cord that exhibited a static deflection of about 16 inches. During the tests, the cold finger component was connected to the cooler by a metal tube, and the electronic power line was extended to controls located outside the chamber. Table 1 lists the BBN instruments employed for the acoustic and vibration monitoring. Except for the transducers and preamplifiers, all of the instrumentation was also located outside the test chamber.

With the electric input to the coolers set at 18 volts, the speed of cooler S/N 001 was 1125 rpm with a current of approximately 2.3 amps, while the speed of cooler S/N 003 was 1510 rpm with a current of about 1.7 amps. These speeds and currents were noted to vary somewhat during the tests as the temperature of the main body increased and the temperature of the cold finger decreased.

Vibration

At CTI's direction, the center of mass of the cooler unit was assumed to be at the intersection of the x-axis (motor axis) with the plane of the center flange. Two accelerometers were mounted on this flange, one on each side of the motor axis. The transducers were oriented in the same direction so to measure both the lateral acceleration and angular acceleration about the appropriate axes. The electrical signals of the transducers were added to obtain lateral acceleration levels, and subtracted to obtain angular acceleration levels. Pictures of the cooler which illustrate the various accelerometer configurations have already been transmitted to CTI.

Table 2 presents the calculated force and torque values for each primary axis of the two cooler units. The procedures for calculating these values from the measured data are given below. Values are given for the two different accelerometer configurations which yield force and torque data about the x axis. This redundancy is necessary in order to obtain data for the y and z axes. The values are in general agreement, although some variations are noted at the lower harmonic frequencies. It is not understood at this time why these variations did occur, or why several values for the y and z axes were considerably higher than the criterion. This may be a result of vibration coupling between the cooler, cold finger, and suspension which have caused the cooler vibration levels to increase. Plots of the vibration measurements are presented in Appendix B.

Force

$$F_i = ma_i \quad \text{where } i \text{ is the } x, y, \text{ or } z \text{ axis}$$

1. Calculate mass of cooler $m = \frac{w}{g}$

$$m = \frac{3.25 \text{ lb}_f}{32.2 \text{ ft/sec}^2} = 0.101 \text{ slugs}$$

2. Convert measured rms acceleration level (total rms level of the in-phase components of the two accelerometers) to actual rms level in dB re 1 g rms.

$$AL_{\text{actual rms}} = AL_{\substack{\text{measured} \\ \text{(addition)}}} - 6 \text{ dB}$$

3. Convert actual rms acceleration level to actual peak acceleration level, assuming sinusoidal motion of the body.

$$AL_{\text{actual peak}} = AL_{\text{actual rms}} + 3 \text{ dB}$$

4. Convert to actual peak acceleration in absolute terms in ft/sec².

$$a = 32.2 \left[10^{\left(\frac{\text{AL actual peak}}{20}\right)} \right] \text{ ft/sec}^2$$

Torque

$$T_i = I_{ii} \ddot{\theta}_i \quad \text{where } i \text{ is the } x, y, \text{ or } z \text{ axis}$$

1. The moment of inertia about each major axis was determined experimentally with a torsional pendulum setup.

I_{xx} = 0.24 slug-in² (motor axis)

I_{yy} = 0.36 slug-in² (piston axis)

I_{zz} = 0.38 slug-in² (orthogonal axis)

bbn

2. Convert measured actual rms level in dB re 1 g rms (total rms level of the out-of-phase components of the two accelerometers) to actual peak acceleration level, assuming sinusoidal motion of the body.

$$AL_{\text{actual peak}} = AL_{\substack{\text{measured}\\ \text{(difference)}}} + 3 \text{ dB}$$

3. Convert to actual peak acceleration in absolute terms in in/sec².

$$a = 386 \left[10^{\left(\frac{AL \text{ actual peak}}{20}\right)} \right] \quad \text{in/sec}^2$$

4. Convert to actual peak angular acceleration in rad/sec².

$$\ddot{\theta} = \frac{a}{L} \text{ rad/sec}^2$$

where L is the distance separating the two accelerometers, 2.88 inches.

5. Calculate torque and convert from slug-in²/sec to in-oz.

* * * * * * * *

We hope that this information is sufficient for your needs. I apologize for the unexpected delay in transmitting these data to you. Should you have any questions or comments concerning this report, please contact me at your convenience.

Sincerely,

BOLT BERANEK AND NEWMAN INC.

James D. Barnes

JDB/kc

bbn

TABLE 2

SUMMARY OF FORCES AND TORQUES CALCULATED FROM FREE BODY ACCELERATION MEASUREMENTS

Cooler S/N 001

	AXIS*	HARMONIC / FREQUENCY (Hz)								CRITERION
		1	2	3	4	5	6	7	8	
		18.75	37.50	56.25	75.00	93.75	112.50	131.25	150.00	
Peak Force (lb_f)	X†	0.29	0.18	0.09	0.11	0.11	0.13	0.16	0.10	0.40
	X	1.02	0.32	0.16	0.11	0.10	0.13	0.23	0.14	0.40
	Y	0.29	0.11	0.04	0.04	0.03	0.07	0.09	0.04	0.40
	Z	0.41	0.06	0.10	0.03	0.02	0.03	0.02	0.04	0.40
Peak Torque (in-oz)	X	127	63.4	25.2	3.2	4.5	3.6	3.6	5.0	15.0
	X	127	63.4	25.2	3.2	4.0	4.0	3.6	5.0	15.0
	Y	67.9	17.1	9.6	2.4	1.9	1.4	0.8	2.2	4.0
	Z	40.6	11.4	6.4	1.6	1.1	1.6	2.3	1.1	4.0

* X - motor axis (I_{xx} = 0.10 slug-in²)
Y - piston axis (I_{yy} = 0.38 slug-in²)
Z - orthogonal axis (I_{zz} = 0.36 slug-in²)
Mass = 0.10 slugs

† Measurements reported for two different mountings for X axis.

Revised 11/10/80

TABLE 3

SUMMARY OF FORCES AND TORQUES CALCULATED
FROM FREE BODY ACCELERATION MEASUREMENTS

Cooler S/N 003

	AXIS*	HARMONIC / FREQUENCY (Hz)								CRITERION
		1	2	3	4	5	6	7	8	
		25.20	50.40	75.60	100.80	126.00	151.20	176.40	201.60	
Peak Force (lb_f)	X†	0.32	0.51	0.13	0.26	0.14	0.29	0.13	0.14	0.40
	X	0.23	0.41	0.13	0.23	0.18	0.29	0.16	0.14	0.40
	Y	0.02	0.23	0.04	0.09	0.09	0.10	0.06	0.07	0.40
	Z	0.14	0.20	0.03	0.04	0.04	0.04	0.13	0.20	0.40
Peak Torque (in-oz)	X	63.4	63.4	4.5	1.6	1.6	1.1	0.9	2.3	15.0
	X	71.1	63.4	4.0	2.0	1.8	0.9	1.0	2.0	15.0
	Y	19.1	34.0	0.9	2.2	1.7	1.4	1.9	6.1	4.0
	Z	5.1	20.3	2.6	2.6	1.6	3.2	1.4	2.6	4.0

* X - motor axis (I_{xx} = 0.10 slug-in²)
Y - piston axis (I_{yy} = 0.38 slug-in²)
Z - orthogonal axis (I_{zz} = 0.36 slug-in²)

Mass = 0.10 slugs

† Measurements reported for two different mountings for X axis.

Revised 11/10/80

50 Moulton Street
Cambridge, MA 02238
Telephone (617) 491-1850
Telex No. 92-1470

Bolt Beranek and Newman Inc.

12 November 1980

CTI Cryogenics
Kelvin Park
266 Second Avenue
Waltham, MA 02254

Attention: Mr. Noel Holland

Subject: Vibration Measurements of CTI Coolers
S/N 002 and CM-4 Prototype
BBN Project No. 154707

Dear Sir:

At the request of CTI Cryogenics, Bolt Beranek and Newman Inc. (BBN) has performed a series of acoustic and vibration measurements on several CTI Model CM-4 cooler units. In July 1980, BBN performed a series of measurements on units S/N 001 and S/N 003; the results of these were documented in BBN's 22 August and 10 November 1980 letter reports to CTI. In October 1980, we carried out acoustic and vibration measurements on cooler unit S/N 002 and vibration measurements on the CM-4 prototype. This letter report summarizes the vibration test procedure and presents the results of the October measurements in a format similar to that of the August report. At CTI's request, a separate report will document the results of the acoustic measurements.

VIBRATION MEASUREMENT PROCEDURE

Each cooler unit was suspended from the ceiling of BBN's anechoic chamber by a soft rubber cord, which exhibited a static deflection of at least 16 inches. Cooler unit S/N 002 was mounted such that the motor axis (x-axis) was horizontal, similar to the configuration employed for unit S/N 001 and 003 tests.

Boston Washington Los Angeles

TABLE 2

SUMMARY OF FORCES (lb) AND TORQUES (in-oz) CALCULATED FROM FREE BODY ACCELERATION MEASUREMENTS

COOLER S/N 002

	AXIS*	HARMONIC/FREQUENCY (Hz)								CRITERION
		1	2	3	4	5	6	7	8	
		21.9	43.8	65.7	87.6	109.5	;31.4	153.3	175.2	
Peak Force (lb_f)	X†	1.02	0.64	0.11	0.08	0.11	0.10	0.11	0.18	0.40
	X	0.57	0.36	0.11	0.11	0.16	0.13	0.13	0.20	0.40
	Y	0.18	0.20	0.05	0.05	0.05	0.03	0.05	0.07	0.40
	Z	0.51	0.20	0.04	0.01	0.02	0.02	0.01	0.04	0.40
Peak Torque (in-oz)	X†	127	56.5	14.2	4.5	2.5	0.6	0.1	1.8	15.0
	X	113	63.4	11.3	5.7	1.8	0.8	<0.3	1.8	15.0
	Y	14.4	9.6	0.7	0.9	0.2	0.5	0.9	0.8	4.0
	Z	10.2	1.3	1.3	0.3	1.4	1.4	1.0	2.2	4.0

*X - motor axis (I_{xx} = 0.10 slug - in²)
Y - piston axis (I_{yy} = 0.38 slug - in²)
Z - orthogonal axis (I_{zz} = 0.36 slug - in²)
Mass = 0.10 slugs

† Measurements reported for two different mountings for X axis. Accelerometers were mounted on Z axis for first set of translational and angular acceleration measurements, and on y axis for second set.

APPENDIX IV

ACOUSTIC NOISE

This appendix contains calculations and test results extracted from Bolt, Beranek and Newman's Technical Report dated 19 December, 1980, verbatim.

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Cambridge, MA 02238
Telephone (617) 491-1850
Telex No. 92-1470

Bolt Beranek and Newman Inc.

19 December 1980

CTI Cryogenics
Kelvin Park
266 Second Avenue
Waltham, MA 02254

Attention: Mr. Noel Holland

Subject: Acoustic Measurements of CTI Coolers
S/N 001, 002, 003, and CM-4 Prototype
BBN Project No. 154707

Dear Sir:

Bolt Beranek and Newman Inc. (BBN) performed a series of acoustic measurements in July 1980 on two CM-4 cooler units, S/N 001 and 003, and in October 1980 on cooler unit, S/N 002. During the test periods, BBN also made vibration measurements on these three units and the Cm-4 prototype unit. Several previous letters to CTI, which are dated 22 August and 10 and 12 November 1980, document the results of the vibration tests. This letter report summarizes the measurement procedures, calculations, and results of the acoustic tests. It is noted that acoustic data for units S/N 001 and 003 have also been presented in the 22 August 1980 letter.

ACOUSTIC MEASUREMENTS PROCEDURE

Each cooler unit was supported by a soft rubber cord from the ceiling of BBN's anechoic chamber. Each unit was mounted such that the motor axis (x-axis) was horizontal and the piston axis (y axis) was vertical. The coordinate axes for which the data are reported here are defined as follows:

- x: Along motor shaft centerline; positive toward power connection.
- y: Parallel to the axis of piston movement.
- z: Orthogonal to the x and y axes; positive away from cold finger connection (which lies nearby on the negative z axis).

Boston Washington Los Angeles

It is noted that these definitions are slightly different than in the August report. The data presented again in this document for units S/N 001 and 003 reflect these changes.

Tables 1 and 2 list the instrumentation used for the tests. The sound pressure levels (SPL's) of each cooler were measured with a microphone located on the major axes at 36 inches from the unit during its operation. After proper calibration of the measurement system, the background noise level due to electrical and other acoustic sources was measured inside the anechoic chamber. It was determined that the background noise did affect the readings of the cooler units in the octave bands centered at 125 and 250 Hz, and occasionally, in the octave band centered at 500 Hz. This caused little concern though, since the SPL's measured with the cooler operating were seen to be well below the criterion SPL's.

Additional data were collected at 18 inches and 36 inches from units S/N 001 and 003 in order to determine the effect of cold finger noise on the measured SPL's. These measurements were obtained without a cover on the cold finger and with an acoustical enclosure around the cold finger. Although the microphone was located at 18 inches and 36 inches from each unit, the distances from the microphone to each cold finger were generally greater than these by 4-12 inches for the x and z axes measurements and 20-36 inches for the y axis measurements.

For the tests of unit S/N 003 in October 1980, CTI installed a protective metal cover over the cold finger section. This also helped to reduce the noise levels of the cold finger, however, it did not eliminate the effect of the cold finger noise upon the measured SPL's. For the purposes of our calculations, the noise emissions of the cooler unit and cold finger were not separated.

ACOUSTIC DATA

Figures 1-3 present the ranges of sound pressure levels calculated at a distance of 5 meters from the three cooling units. Figures 1 and 2 also show the SPL's measured with an acoustical enclosure around the cold finger. These SPL's were extrapolated from the data obtained at 36 inches from the main body along its major axes (motor, piston, orthogonal). To show comparison with the acoustic criterion, the SPL's were calculated at 5 meters by employing the following equation:

$$SPL_{(5m)} = SPL_{(36\ in.)} - 20\log_{10}\left\{\left(\frac{5m}{36\ in.}\right)\left(\frac{39.37\ in.}{m}\right)\right\}$$

CTI Cryogenics
Attn: Mr. Noel Holland
BBN Project No. 154707
Date: 19 December 1980
Page: 3

The data set for cooler S/N 001 includes measurements performed on two different days since the first day's tests were limited by cooler motor problems. However, some measurements were performed with the cold finger covered and uncovered, and Figure 1 includes these data. The separate plots of the sound pressure levels for each unit are presented in the Appendix.

* * * * * * * * * * *

Please contact me at your convenience with any questions or comments after you have had an opportunity to review this report.

Sincerely,

BOLT BERANEK AND NEWMAN INC.

J. Barnes

James D. Barnes

JDB/kc

bbn

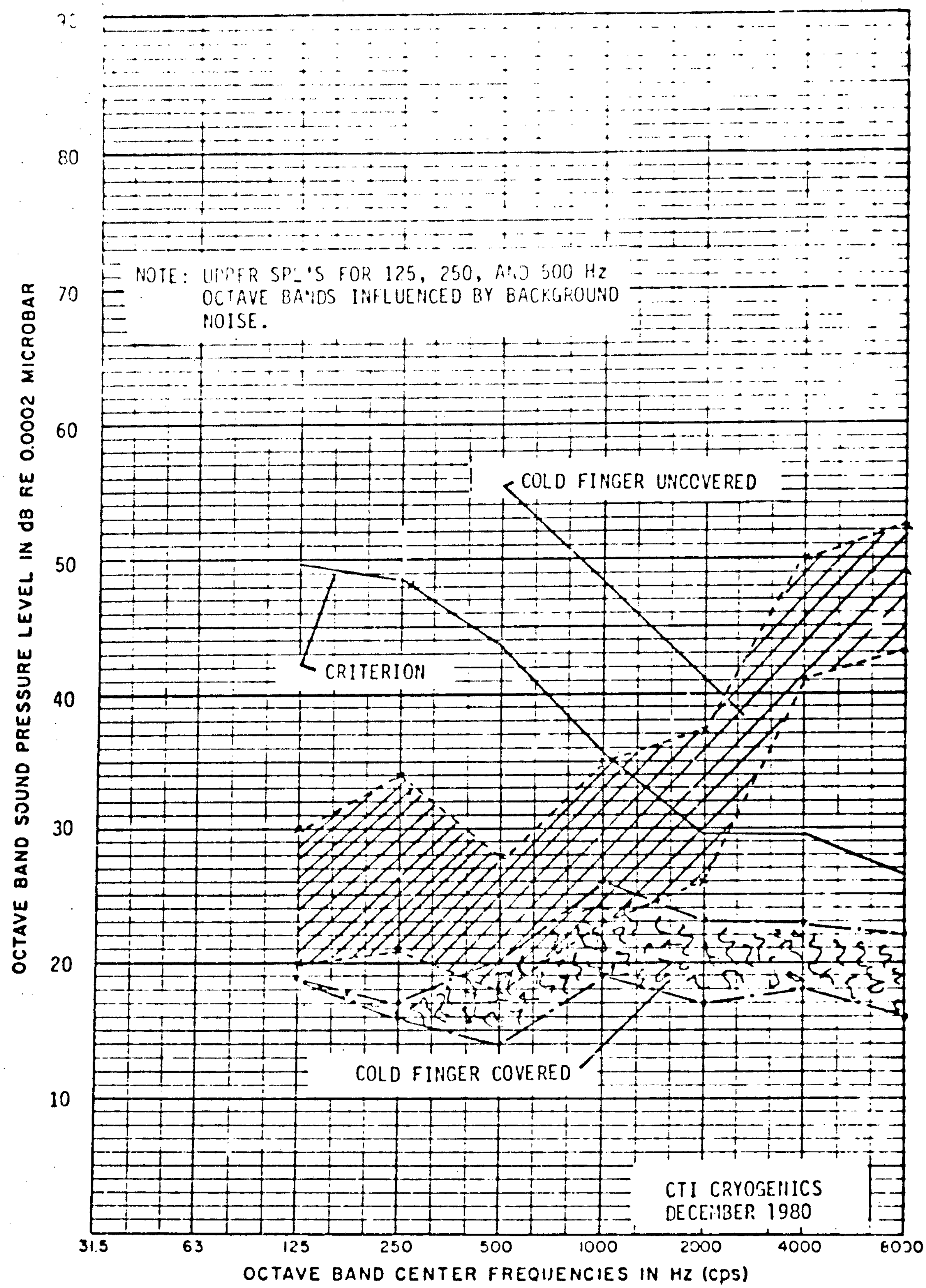


FIGURE 1. SOUND PRESSURE LEVELS AT 5 METERS FROM COOLER S/N 001 (CALCULATED FROM SPL MEASUREMENTS AT 36 INCHES).

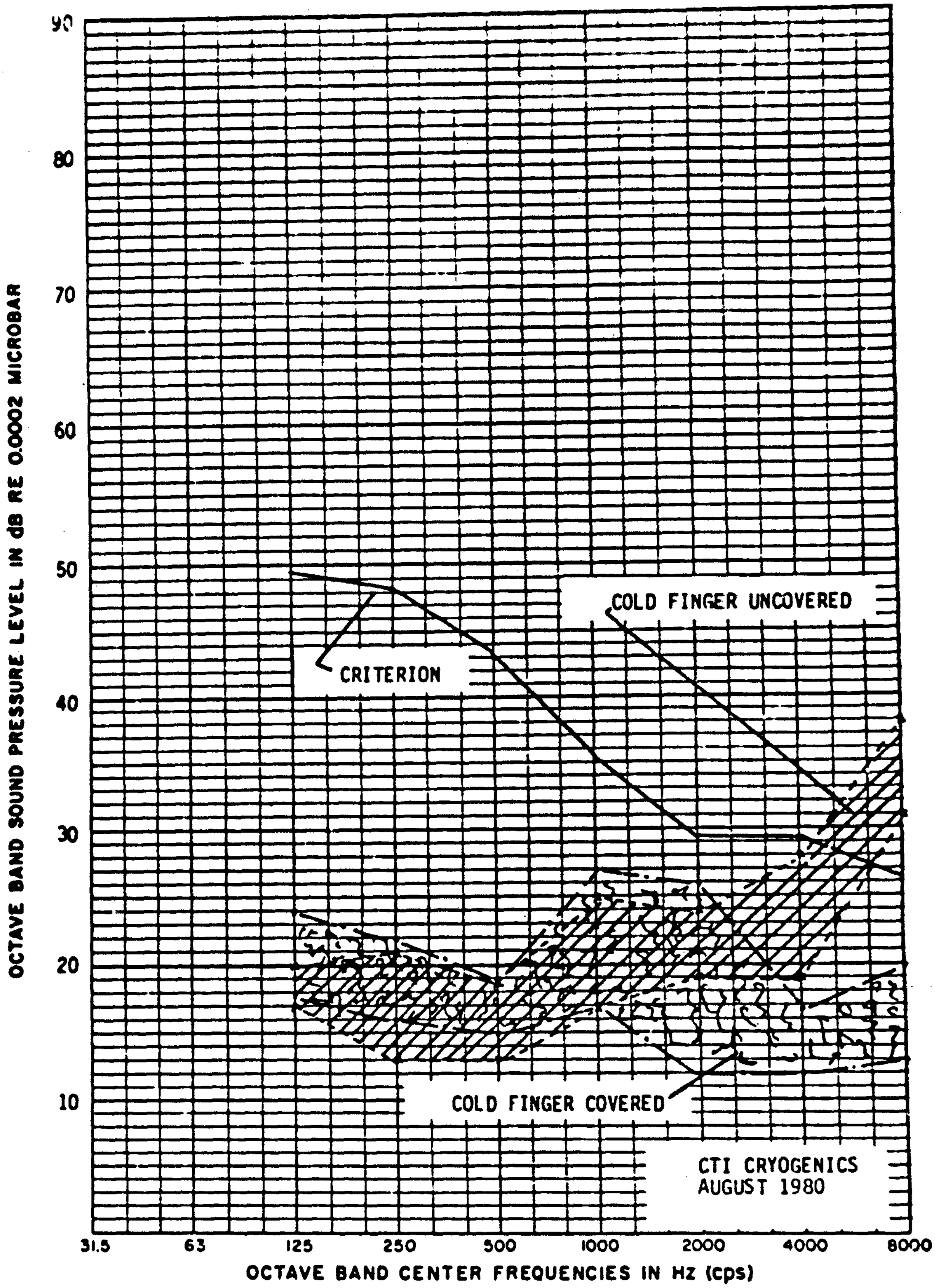


FIGURE 2. SOUND PRESSURE LEVELS AT 5 METERS FROM COOLER S/N 003 (CALCULATED FROM SPL MEASUREMENTS AT 36 INCHES).

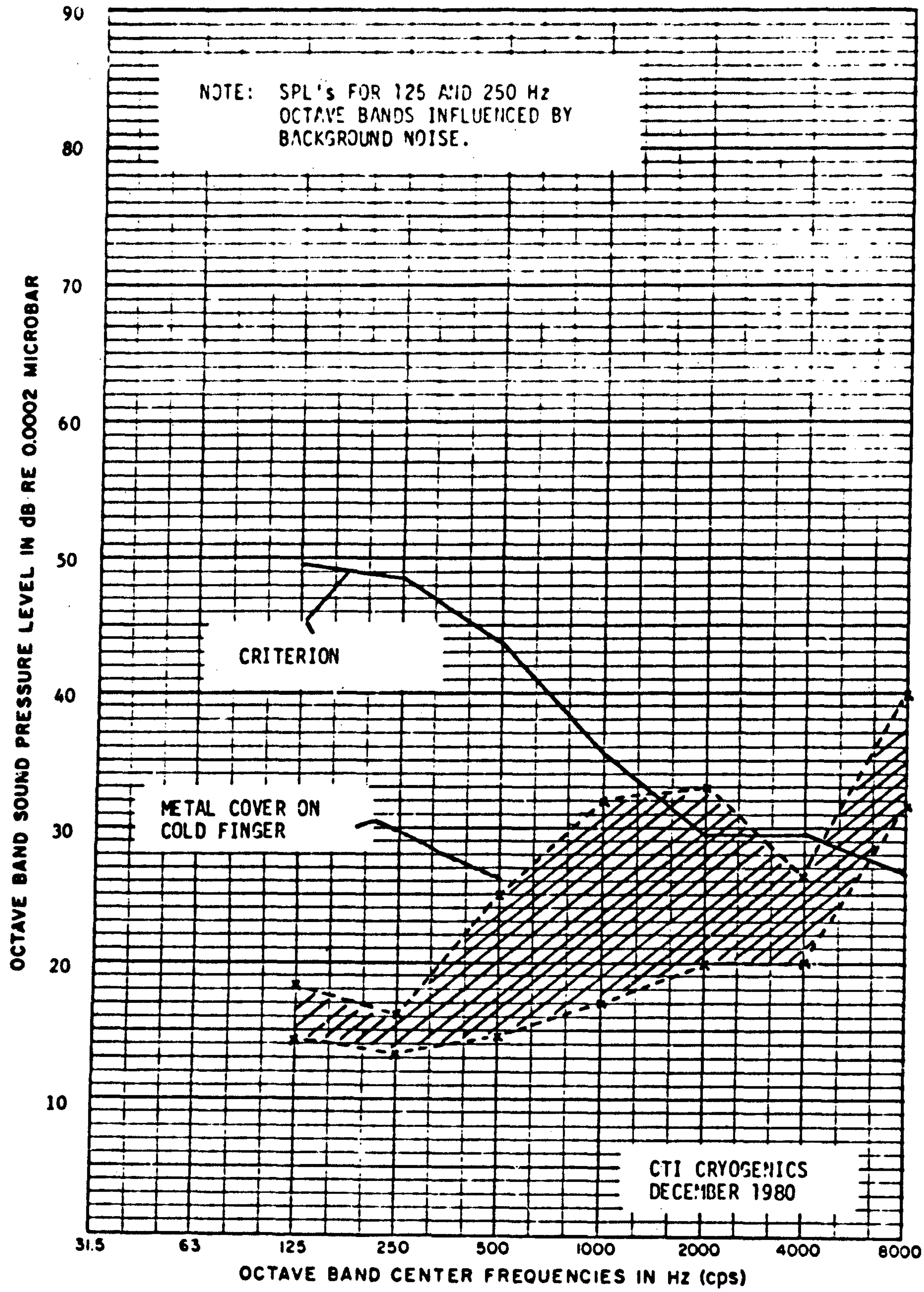


FIGURE 3. SOUND PRESSURE LEVELS AT 5 METERS FROM COOLER S/N 002 (CALCULATED FROM SPL MEASUREMENTS AT 36 INCHES).

APPENDIX V

PERFORMANCE TEST PLAN

NV & EOL 1.0 WATT COOLER

APPLICATION		REVISIONS			
NEXT ASSY	USED ON	REV	DESCRIPTION	BY-DATE	APPROVED
		—	INITIAL RELEASE		

PERFORMANCE TEST PLAN

MFLD AUG80

REV																			
SHEET	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
REV. STATUS	REV.																		
OF SHEETS	SHEET	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		

PROPRIETARY AND CONFIDENTIAL

THIS DRAWING IS NOT TO BE REPRODUCED OR USED TO MAKE ANY APPARATUS BASED THEREON WITHOUT PRIOR WRITTEN AUTHORIZATION FROM HELIX TECHNOLOGY CORPORATION

		DATE
PREPARED	NJHolland	3/80
CHECKED	M. C. H.	6/17/80
APPROVED	A Clint	17 June 80
APPROVED		
APPROVED		

CTI-CRYOGENICS
Waltham, Massachusetts USA

HELIX
A Helix Company

PERFORMANCE TEST PLAN: NV & EOL 1.0 WATT COOLER

SIZE	FSCM NO	DWG NO.	REV.
A	31949	3543 600	
SCALE		SHEET 1 OF 13	

1.0 SCOPE

This specification establishes the procedures for performance testing of the NV & EOL 1.0 Watt Miniature Cooler.

2.0 APPLICABLE DOCUMENTS

CTI-CRYOGENICS

D8076001 - Compressor Interface

D8076002 - Expander Interface

Military Specifications

MIL-Q-9858A	Quality Program Requirements
MIL-STD-129E	Marking for Shipment and Storage
MIL-STD-781B	Reliability Tests, Exponential Distribution
MIL-STD-810B	Environmental Test Methods
MIL-C-45662	Calibration Standards

Non-Government Documents

ANSI-S1.11-1971 Specification for Octave, Half-Octave, and Third Octave Band Filter Sets (American National Standards Institute, Inc., 1430 Broadway, New York, NY 10018).

3.0 REQUIREMENTS

3.1 General

Prior to acceptance testing, the NVL 1.0 Watt Cooler shall be pressurized to 550 PSIG with helium gas and leak tested in a bell jar. The maximum allowable leak rate shall not exceed 1 x 10^{-7} scc/sec from -62°C to +71°C ambient temperatures.

3.1.1 The compressor and expander assembly shall be tested as a system.

3.1.2 The cold finger shall be instrumented in accordance with paragraph 3.9 of this specification.

3.1.3 Unless otherwise specified, performance testing will be conducted at +23°C ± 4°.

SIZE	FSCM NO.	DWG NO.	REV
A	31949	A3543 600	
SCALE		SHEET 2 of 13	

3.2 PREPARATION FOR TESTING

3.2.1 Attach the instrumentation to the cold finger in accordance with paragraph 3.9 of this specification.

3.2.2 Assemble the cold finger into the test vacuum jacket.

3.2.3 Purge and charge the system in accordance with CTI-CRYOGENICS specification A3543621

3.2.4 Evacuate the test Dewar to a vacuum level of 1×10^{-4} Torr or better.

3.3 ACCEPTANCE TEST CONDITIONS

All performance tests shall be conducted under the following conditions:

3.3.1 Ambient Temperature
$23 \pm 4°C$

3.3.2 Pressure
Standard atmospheric pressure at ground level.

3.3.3 Humidity
Room ambient

3.3.4 Electrical Power
18.5 ± 0.5 volts d-c.

3.3.5 System Charge Pressure
550 PSIG. Helium gas (99.995% pure)

3.3.6 Test Vacuum Level
1×10^{-4} Torr or better

3.3.7 Heat Sinking
The compressor shall be heat sunk to an aluminum support bracket using thermal grease. The test chamber circulating fan shall provide forced cooling air for the cooler.

3.4 PERFORMANCE REQUIREMENTS

The NV & EOL 1.0 Watt Miniature Cooler must meet the following performance criteria when tested under the conditions outlined in paragraph 3.3 of this specification:

SIZE	FSCM NO.	DWG NO.	REV
A	31949	A3543 600	
SCALE		SHEET 3 of 13	

Amb. Temp.	Cooldown Time	Net. Refrig. @ 80K	*Power
23°C	10 mins. to 100K	1.00 Watt	60 watts max.
23°C	15 mins. to 80K		

*Steady state operating conditions

3.4.1 Performance Test Procedure

The cooler shall be started at an ambient temperature of 23°C for 30 mins. without an electrical load applied.

After operating for 30 minutes, apply a 1.0 watt electrical load to the cold finger. Allow the cooler to operate in this mode for four (4) hours. After the four hour period, remove the heat load and operate for an additional four hours, then shut down.

3.5 ACOUSTIC NOISE

The cooler shall be set up for operation in an area where the background noise level is at least 10db below the sound level to be measured. The cooler shall be operated and sound pressure measurements made made with the cooler oriented to record the maximum level. Measurements shall be made with an octave-band analyzer with characteristics which comply with ANSI Specification S1.11-1971. The maximum sound pressure levels when measured at a distance of five (5) meters shall not exceed the noise values tabulated below:

Sound Pressure Values

Center Frequency - Hz	Octave Band - Hz	*Max Sound Press. Level (db)
125	87-175	49.5
250	175-360	48.5
500	350-700	43.5
1000	700-1400	35.5
2000	1400-2800	29.5
4000	2800-5600	29.5
8000	5600-11,200	26.5

*Reference 0.0002 microbars.

3.6 SELF-INDUCED VIBRATION TEST

Vibration Output- The cooler shall be suspended such that the operating frequency of the cooler is much higher than the natural frequency of the suspension material. Accelerometers shall be mounted on the cooler to measure the acceleration on the three major axes and the angular acceleration about each axis. The cooler, fully charged, shall be turned on 15 minutes before measurements are taken. Peak forces derived from the expression F=MA, where F is the peak force, M is the cooler mass, and A is the measured acceleration at a given frequency, shall not exceed 0.4 pounds (semi-amplitude) for any of the first eight (8) harmonics. Peak torque derived from the expression T =I, where T is the peak torque, I is the moment of inertia about the principal axis, and is the measured angular acceleration for the applicable axis, at a given frequency, shall not exceed 15.0 in-oz. semi-aplitude (Design Goal) for any of the first eight (8) harmonics of the motor axis and 4 in-oz (semi-amplitude) for any of the first eight (8) harmonics of the other two axes.

3.7 ENVIRONMENTAL TESTS

The NV & EOL 1.0 Watt cooler shall be subjected to the environmental tests as outlined in the following paragraphs:

3.7.1 Temperature Shock

The cooler shall be subjected to Method 503 MIL-STD-810B. The temperature of steps 1 and 4 shall be +68.3°C.

3.7.2 High Temperature

The cooler shall be subjected to the test of Method 501, Procedure II of MIL-STD-810B. The temperature of steps 4 and 5 (highest operating temperature) shall be +71°C. Repeat steps 1 and 8 except that the temperature of step 2 (highest temperature) shall be +71°C, the length of time during step 3 shall be 30 minutes, and the temperature of steps 4 and 5 (highest operating temperature) shall be +71°C.

3.7.3 Low Temperature

The cooler shall be subjected to the test of Method 502, Procedure I of MIL-STD-810B. The storage temperature (step 2) shall be -62°C and shall be maintained until temperature stabilization of the cooler is reached. Low operating temperature (step 4) shall be -54°C.

3.7.4 Shock

The cooler shall be subjected to the condition of MIL-STD-810B, Method 516.1, Procedure IV, Figure 516.1-1 (100 g at 11 milliseconds) and procedure V.

3.7.5 Vibration

The cooler shall be subjected to the condition specified in MIL-STD-810B, Method 514.1, Procedure VIII, Figure 514.1-6, Test Level W, and Procedure 1, Figure 514.1-1. Test Level M.

3.7.6 Acceptance Criteria

The NV & EOL 1.0 Watt cooler must meet the performance requirements of para 3.4 and Figure II of this specification.

3.8 LIFE TEST

The NV & EOL 1.0 Watt Cooler shall be subjected to a 1000 hour life test in accordance with the life test cycle shown below.

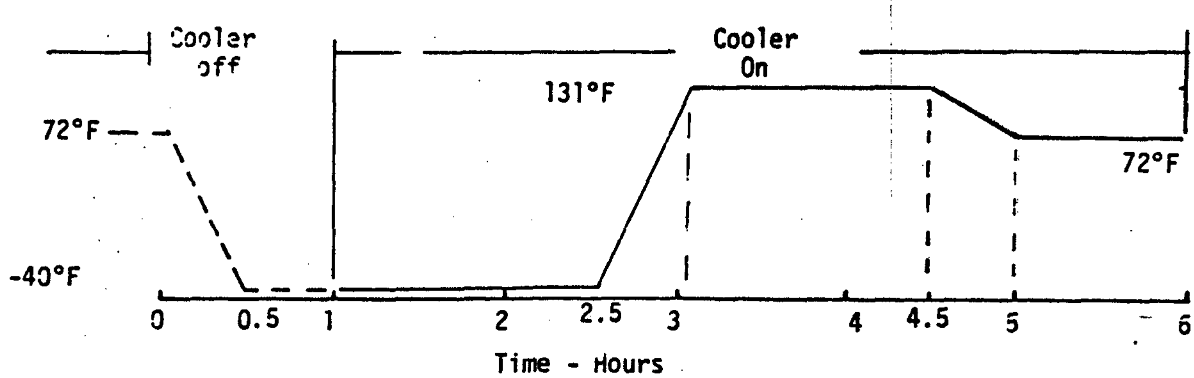


Figure 1.

SIZE	FSCM NO.	DWG NO.	REV.
A	31949	43543 600	
SCALE		SHEET 6 of 13	

During the life test the cooler shall be subjected to a two (2) g vibration input at a nonresonant frequency for 10 minutes each operating hour. The specified 1000 hour MTBF (θ_0) shall be demonstrated in accordance with MIL-STD-781B, Test Plan IV A.

3.9 INSTRUMENTATION REQUIREMENTS

For all acceptance tests, the NV & EOL 1.0 Watt Cooler shall be instrumented in accordance with this paragraph.

3.9.1 Temperature Sensor

A Silicon Diode. Lakeshore P/N DT-500 FP will be used in monitoring the cold finger temperature. The Diode will be attached to a 11 gram copper mass.

The output of the Silicon Diode will be monitored on a high impedance digital voltmeter and recorded on an Esterline Angus single pen recorder Model No. MS 411B or equivalent.

3.9.2 Resistance Heater

A wire wound resistance heater will be attached directly to the 11 gram copper mass. An appropriate power supply will be used in conjunction with the heater.

3.9.3 Thermocouples

Copper Constantan thermocouples will be used to monitor the ambient temperature and also, the compressor motor housing.

3.9.4 Vacuum Equipment

The test Dewar shall be evacuated through a 3/4" I.D. stainless steel flexible hose attached to a VEECO high vacuum pumping station Model No. VS-9 or a CTI-CRYOGENICS cryopump.

3.9.5 Power Supply

An 18 VDC power supply, Hewlett Packard Model 6217A with appropriate D.C. volt and ammeter will be utilized for supplying the proper input voltage.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 INSTRUMENTATION CALIBRATION

All regularly scheduled maintenance and calibration of test equipment is to be performed in accordance with the provisions of MIL-C-45662.

4.1.1 Electronic Recorders

The output of all thermocouples shall be recorded to an accuracy of 1 percent full scale.

4.1.2 Heater and Power Supply

The heater loads shall be supplied from a stablized D.C. power supply. The heat load in watts shall be set and maintained to within 5 percent of the specified value.

4.1.3 Vacuum Indicators

The vacuum indicator system (thermocouple gauge, and vacuum control) shall be adjusted daily per the manufacturer's instructions. The vacuum gauge control shall be calibrated at least once a year.

4.1.4 Electrical Meters

All ammeters and wattmeters shall be accurate to within 2 percent of full scale. All voltmeters shall be accurate to within 1 percent of full scale.

4.2 TEST DATA

Log sheets are to be maintained during all acceptance tests. All pertinent data and system information shall be recorded on the log sheet. One complete set of data shall be recorded upon cooldown to 100K, then at least every 15 minutes thereafter. Three (3) copies of system performance data are to be shipped with each unit. The original log sheets are to be filed at CTI-CRYOGENICS.

4.3 TEST APPROVAL

All test results and performance data shall be reviewed prior to shipment and approved by the Product Engineer, Quality Control, and the Source Inspector, if required. These acceptances and approvals are mandatory and must be received before a system can be shipped.

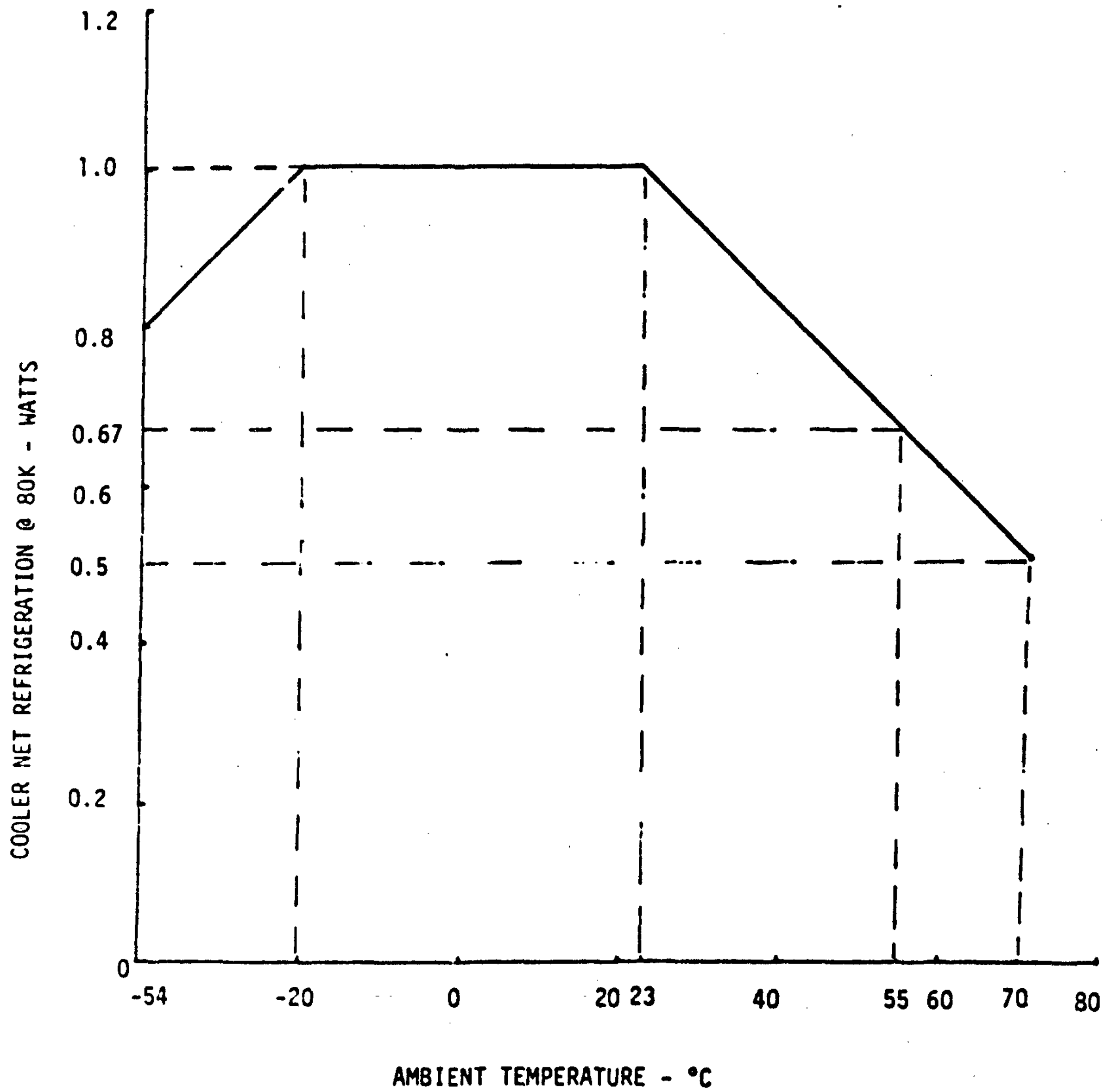


Figure II.

SIZE	FSCM NO.	DWG NO.	REV
A	31949	A3543600	
SCALE		SHEET 9 of 13	

DATE:____________________

TECHNICIAN:____________________

COMPRESSOR S/N____________________

DISPLACER S/N____________________

EXPANDER S/N____________________

*Includes interconn line

COMPRESSOR WT.____________________OZS.

DISPLACER WT.____________________GMS.

*EXPANDER WT.____________________OZS.

HARNESS WT.____________________OZS.

REGENERATOR TYPE____________________

CLEARANCE SEAL MATERIAL____________________

DISPLACER SEAL____________________

MOTOR TYPE____________________

DISPLACER SEAL FRICTION____________________

REGENERATOR FLOW @ 10PSI____________________

REGENERATOR RUNOUT____________________

COMP. BRG. LUBRICATION____________________

COMP. PISTON SEAL____________________

COMP. PISTON SEAL FRICTION____________________

INTER. CONN. LINE LENGTH____________________

SYSTEM LEAK RATE____________________ scc/sec.

SIZE	FSCM NO.	DWG NO.	REV
A	31949	A3543600	
SCALE		SHEET 10 of 13	

NV & EOL 1.0 WATT COOLER - PERFORMANCE TEST PLAN

COOLER S/N ______________________

DATE ______________________

TECHNICIAN ______________________

CHARGE PRESSURE ______________ PSIG

COOLDOWN TO 80K ______________ MINS.

COLD TIP NO LOAD TEMP. ______________ K

REFRIG. CAP. @ 80K ______________ WATTS

Date / Time	Temp -°F	Cold Tip Temp K/V	Load-Watts	System Power			VAC	Mtr. Temp / RPM
				V.D.C.	AMPS	Watts		

SIZE	FSCM NO	DWG NO	REV
A	31949	A3543600	
SCALE		SHEET 11 of 13	

NV & EOL 1.0 WATT COOLER - PERFORMANCE TEST PLAN

Date / Time	Temp -°F	Cold Tip Temp K/V	Load - Watts	System Power			VAC	Mtr. Temp / RPM
				V.D.C.	AMPS	Watts		

Approvals:

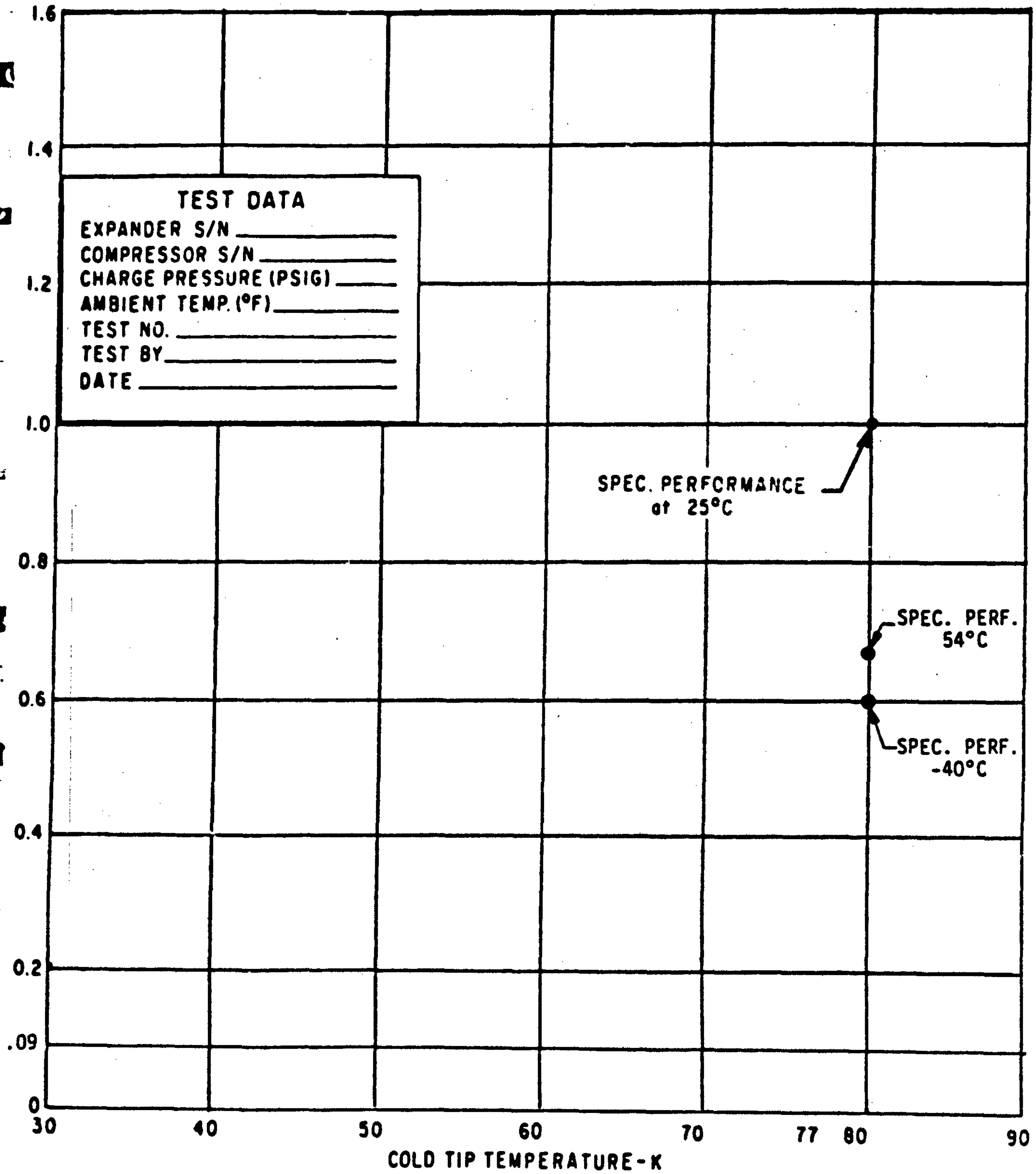
CTI Project Engineer ______________________________ Date __________

CTI Q.C. Engineer ______________________________ Date __________

Source Inspector ______________________________ Date __________

SIZE	FSCM NO.	DWG NO	REV
A	31949	A3543600	
SCALE		SHEET 12 of 13	

PERFORMANCE TEST RESULTS
NV & EOL 1.0 WATT COOLER



COLD FINGER TEMPERATURE VS. NET REFRIGERATION

A3543600
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